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CONTENTS

Page

Problems of Underwater Illumination, by W. D. Chesterman, B.Sc., F.Inst.P., and J. B. Collins, B.Sc. (Eng.), *(Member)* 193

Additions to list of Members - - 226

Register of Lighting Engineers - - 226

Comfortable Lighting—Its Study and Realization, by L. C. Kalff, C.E., Arch. B.N.A. - - - - 227

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Problems of Underwater Illumination

By W. D. CHESTERMAN, B.Sc., F.Inst.P., and J. B. COLLINS, B.Sc. (Eng.) *(Member)*.

Summary

Visibility and lighting problems under water are discussed in relation to the known properties of the medium. Measuring instruments for use on the actual location are described. A photographic method of examining the visibility problem in daylight was used and range curves for targets of different reflection factor in water of varying clarity are derived from contrast measurements. The requirements of artificial lighting in water of poor clarity have been studied, the necessary equipment using mercury and sodium vapour discharge lamps has been developed experimentally, and techniques of its use in the sea have been learnt. The use of high speed photography for some special underwater problems requires the use of flash discharge tubes, and the application of these to propeller cavitation research is described.

(1) Introduction

This paper describes the methods used, and results of work carried out on visibility and lighting problems concerning photography in the sea. The main object of the research was to discover the best conditions for visibility of an object as seen by an underwater camera, and the effect on the visibility of varying these conditions. The problems of "seeing" an object by eye, or by a film or television camera, are in principle the same under water as in air, but the effect of the absorbing and scattering power of the medium itself on attenuation of light and degradation of contrast is usually much greater.

The problems presented by a medium which must be rigidly excluded from the electrical and working parts of any apparatus, and in which is is only possible to exist with the aid of a special supply of air, have been overcome by application of standard techniques of submarine engineering and diving. The illuminating engineering investigation only is described here in the belief that the similarity in principle and difference in degree and practice with the more usual problems in illuminating engineering may perhaps make this account of general interest, as well as of some value to those who have special interests in this field.

The purely photographic problems have been discussed elsewhere[1] and are only introduced into this account in so far as they affect the illuminating engineering aspects or where the photographic method forms an essential part of the technique of investigation.

The investigation concentrated at first on visibility under daylight conditions, as daylight forms the almost universal aand most convenient source of light for underwater photography, and the information gained under these conditions indicated the direction that the work on artificial lighting should take. Later, it was possible to extend the work to the special problem of lighting for high-speed photography.

(2) Optical Properties of Sea Water

Sea water as an optical medium has much in common with air; it is essentially a transparent medium with material in suspension which both scatters and absorbs light. In very clear water, the light is scattered mainly from the water molecules

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themselves, and since for molecular scatter the variation of scatter intensity with wave-length is given by the Rayleigh law (i.e., scatter intensity varying inversely as the fourth power of the wave-length), this results in the scattered light having a blue colour, for the same reason that clear air (i.e., the clear sky) appears blue.

The important optical properties of sea water from the point of view of lighting for underwater photography are attenuation, scatter function, spectral transmission, and polarisation.

The difference in magnitude of the attenuation properties of air and water is indicated by the fact that clear air may have an attenuation coefficient* of 7×10^{-6} per ft., whereas a sample of carefully filtered distilled water has been measured to have an attenuation coefficient of 1.1×10^{-2} per ft. at a wave-length of 460 mμ. Visibility in air with an attenuation coefficient of 7×10^{-6} per ft. is 100 miles, whereas visibility in air with an attenuation coefficient of 1.1×10^{-2} per ft. is only 355 ft., and this can be assumed to be the maximum possible visibility in clearest water, falling to a foot or so in most harbours, and a few inches in really dirty locations.

In clear smoke-free air the attenuation is due almost entirely to scattering; it is only contamination by industrial smoke which causes absorption, but in clear water, at a wave-length of 550mμ scattered light may only account for from one-fifth to one-half of the total attenuation, the remainder being due to absorption. Data found by Hulburt[2] are given in Fig. 1. With distilled water, and clear coastal water, the proportion of attenuation due to absorption is slightly lower in the green and blue regions of the spectrum than at 550mμ, but increases greatly in the orange and red regions.

(2.1) Scatter Function

Hulburt[2] has also measured the distribution of scatter intensity of samples of sea water, and results for three samples are shown in Fig. 2. These curves are very similar in shape to those obtained in air.

It will be seen that all samples exhibit high forward scattering and lower back scattering, with a minimum at right-angles to the direction of the incident light. The high forward scatter shown in these curves is characteristic of large particle scatter, but the pronounced minimum value at 90 deg. is characteristic of small particle scatter, which seems to indicate that particles of widely different sizes are present, some comparable with the wave-length of light, and some much larger.

(2.2) Spectral Transmission

The spectral transmission curves of distilled water and some coastal waters are given in Fig. 3. It will be seen that distilled water has a high transmission to light in the blue and blue-green region of the spectrum, but the transmission drops fairly rapidly in the orange and red, and very rapidly in the ultra-violet and infra-red regions. Clear oceanic water has a transmission not very greatly below that of distilled water, but as the coast is approached the transmission drops (more at the blue end than the red), and the wave-length of maximum transmission changes to the green or yellow region.

The colour changes resulting from the changes in spectral transmission of the water are a matter of common experience for those who have travelled by sea through the clear-water regions (notably the Mediterranean or Pacific). The molecular scattering in very clear water produces a deep-blue colour, while as the number and size of particles suspended in the water increases, the scattering becomes less selective, and the effect of absorption at the red and blue ends of the spectrum gives the sea a pale-green colour.

The spectral transmission curves of different waters give an indication of the type

* Attenuation coefficient (a) is defined by the expression $a =$ log T, where T is the fraction of light transmitted through unit depth of the medium.

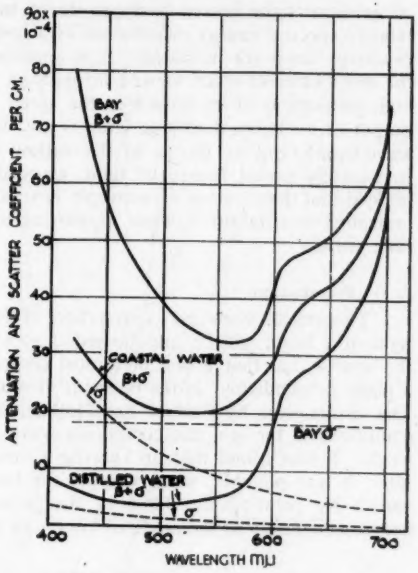


Fig. 1. Absorption and scattering of water samples (From Hulburt (2)).

σ = Scattering coefficient.

β = Absorption coefficient.

$(\sigma+\beta)$ = Total attenuation coefficient

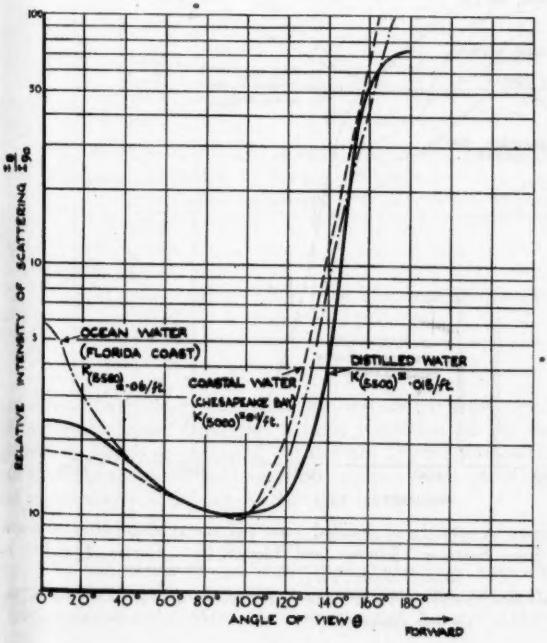


Fig. 2. Polar distribution of relative intensity of scattered light in water.
(From Hulburt (2)).

of artificial light source likely to be of most value under water, and in Fig. 3, the relative spectral energy distribution of a tungsten filament lamp and a mercury vapour discharge lamp are indicated. It is apparent that the mercury vapour source will be the more efficient when viewed through an appreciable water path, on account of the high proportion of its output in the green and yellow regions of the spectrum. The output of a sodium discharge lamp is not shown, since it is practically all at one single wave-length, but as this is in the yellow it would be expected that it would be a particularly useful source of light, especially in less clear waters. It will also be noticed that these curves drop steeply beyond the violet and red regions of the spectrum, indicating that lighting systems employing ultra-violet or infra-red radiations will be of little value.

(2.3) Polarisation

Theoretical work on polarisation of light in liquids indicates that the scattered light in a beam will be unpolarised if viewed looking directly towards or away from the source, but that it will be almost completely polarised (with the electric vector in a plane perpendicular to the beam) if viewed in a direction at right-angles to the beam. The results given by Dawson and Hulburt[4] are shown in Fig. 4. For normal working conditions in the sea, this conclusion was confirmed experimentally during the present work. It was found that on viewing a beam of light in water through a "Polaroid" filter, it was possible, when viewing the beam at right-angles to the axis, to make it vanish by rotating the filter to the appropriate angle. Unfortunately, this effect decreased sharply as the angle of view was altered from the normal, and when viewing

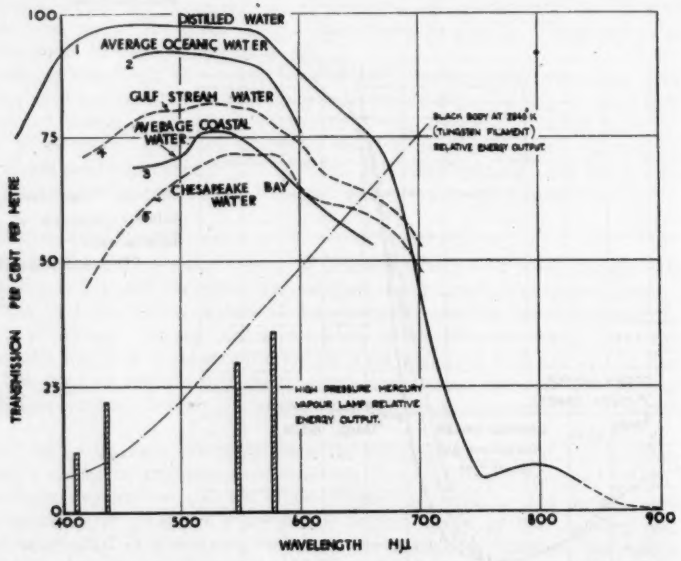


Fig 3. Spectral transmission curves of natural and distilled water and energy distribution of sources (Curves 1, 2 and 3 are from Sverdrup, Johnson and Fleming (3). Curves 4 and 5 are from Hulburt (2)).

(No scales are given for the relative energy of black body and mercury discharge sources as they are not comparable).

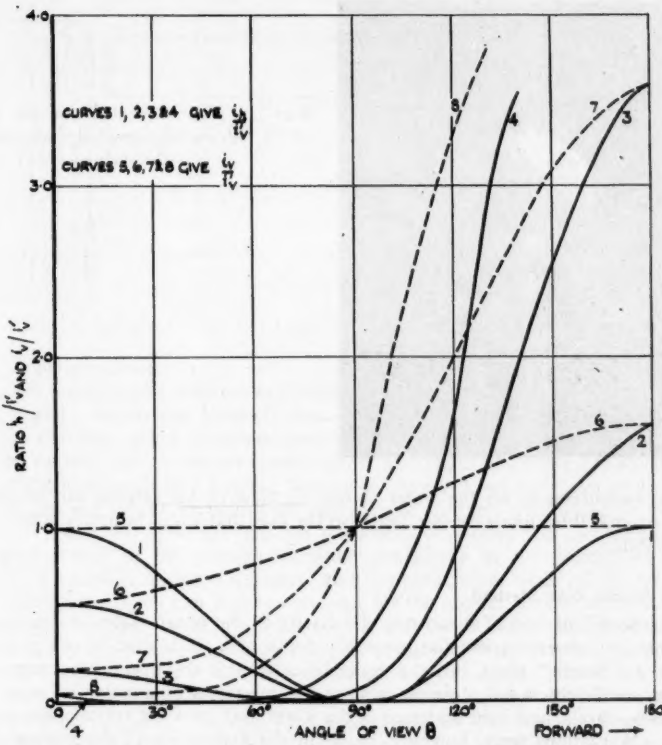


Fig. 4. Theoretical relative intensity of polarised components of scattered light in liquids. (From Dawson and Hulburt (4)). For horizontal beam:—

i_v = Component scattered at angle θ, with electric vector vertical.

i_v' = ,, ,, ,, ,, 90°, ,, ,, ,, ,,

i_h = ,, ,, ,, ,, θ, ,, ,, ,, ,,

Particle sizes:—

Curves 1 and 5—Radius small with respect to wavelength λ;

,, 2 ,, 6—Radius = λ/6·67;

,, 3 ,, 7— ,, = λ/4·28;

,, 4 ,, 8— ,, = λ/3·59.

an object from near the source (or the source from near the object), no effect could be obtained apart from the natural reduction of the brightness of both beam and object by about 60 per cent. It did not appear, therefore, that the use of polarisation to elminate scattered light would be of any value, since only very rarely is the direction of view exactly at 90 deg. to the light beam.

(3) The Present Methods of Study

The properties of sea water discussed so far have all been measured by workers in the laboratory, on samples collected from the sea, carefully transported and kept in special containers. Most of these workers, however, have emphasised the desirability

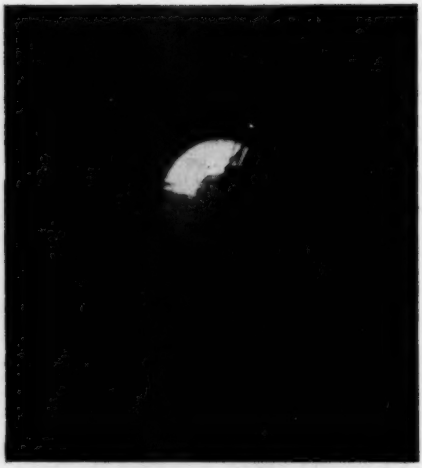


Fig. 5. 200cm. 'Secchi' type disc at depth of 10 fathoms photographed from just below the surface.

of making measurements on the water *in situ*, in view of the settling out of particles, the decay or growth of living matter, and also the fact that water becomes contaminated in glass vessels.

(3.1) The Secchi Disc Method

The standard method of measuring the clarity of the ocean water *in situ* has been, until recently, by observing the disappearance depth of a white disc 30 cm. in diameter (known as a "Secchi" disc), but the dependence of this disappearance range on the attenuation coefficient is not a simple law, as the questions of angular subtense at the eye, brightness levels, and light scattered in the water and from the surface, are involved.

Some observations were, however, made in the early days of the present investigation, and photographs of a 200 cm. diameter disc painted in a pattern of white, grey, and black, have been taken from just below the surface, with the disc lowered to depths as great as 16 fathoms (96 ft.). Fig. 5 shows a photograph taken at 10 fathoms in which the form and pattern of the disc are still clearly seen. This method gives an indication of the visual ranges to be expected, but for the present investigation a more definite physical measurement was required.

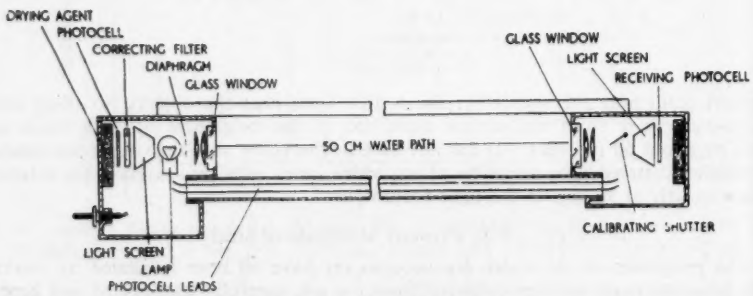


Fig. 6. U.S. Navy hydrophotometer.

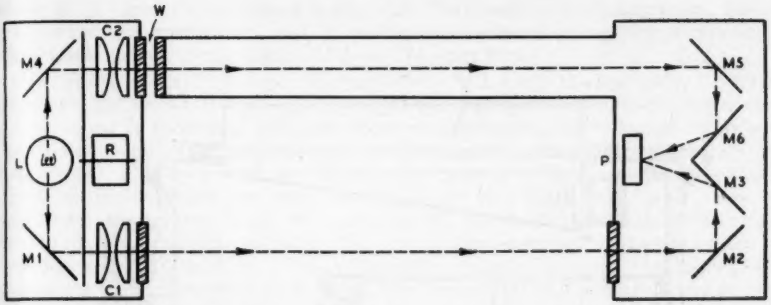


Fig. 7. Experimental two-path hydrophotometer for transmission measurements.

(3.2) The Hydrophotometer

A more fundamental instrumental method of measuring the clarity of sea water has been used by Atkins and Poole[5], who derived attenuation coefficients for water in the English Channel, using photo-electric cells to measure the illumination due to daylight at the surface and at various depths below it. There are, however, advantages in an instrument which will give a direct reading of the clarity of the water at a particular point, and an instrument including its own source of light and using photo-electric cells carefully screened from daylight has since been developed and has been employed as the main source of information on water conditions in the present work. This instrument is called a hydrophotometer, and a modification of a model lent by the United States Navy (shown in Fig. 6) was used for the greater part of the investigation.

A model developed by R. B. Phillips[6], of the Royal Naval Scientific Service, is illustrated in Fig 7. In this, light from the source (L) is divided into two parallel paths. These paths are interrupted alternately about every two seconds by a rotating opaque disc (R) with a suitable sector cut out. One light path (L, M_1, C_1, M_2, M_3, P) is through water, the other (L, M_4, C_2, M_5, M_6, P) is through air. In the " air " path, a short water path (W) equalises the number of air/glass and glass/water surfaces in each path. The collimating lenses (C_1 and C_2) focus the beams on to the mirrors (M_2, M_3, M_5, M_6) which redirect them on to the rectifier type photo-electric cell (P). One light source and one photo-electric cell only are used in order to eliminate troubles due to drift in the cell, thermo-electric effects, and voltage change on the lamp.

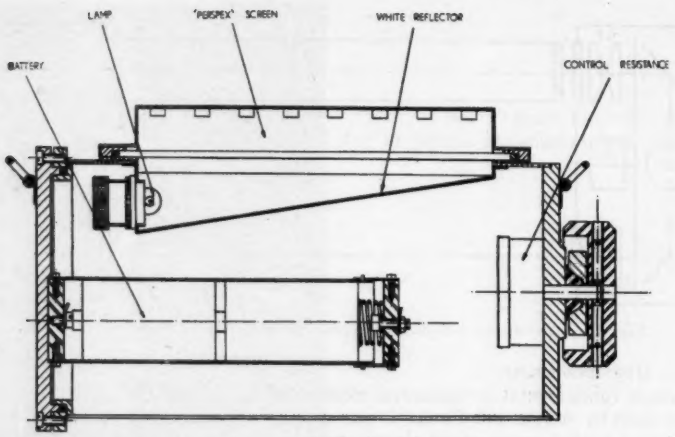
A micro-ammeter in the photo-cell circuit gives two readings for each revolution of the disc shutter—one for each path; the transmission of the water per unit distance is calculated from the ratio of the two readings. The insertion of filters permits transmission measurements in selected regions of the spectrum to be made directly.

Both of these instruments measure the light transmission through half a metre of water. For this reason, the experimental results were expressed in terms of transmission per half metre. For convenience and comparison with other work in turbid media, however, they have been converted into attenuation co-efficients.

(3.3) Submersible Brightness (Luminance) Meter

Since contrast is the governing factor in visibility, it was necessary for any controlled experimental work, to construct an instrument which could be used under water by an observer in a diving helmet or eye mask.

This instrument was constructed on a well-known principle[7] using several spots of graded brightness on a transparent acrylic screen, ¼-in. thick and edge lit from one end by a lamp inside the water-tight box into which it was sealed. The bright spots were obtained by notching the screen at 45 degrees at intervals along its length, and



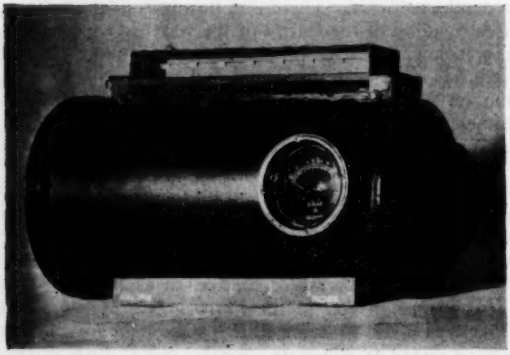


Fig. 8(a) and (b). Underwater exposure-meter.

painting the notches white. The instrument is shown in Fig. 8. It is operated by miniature nickel-iron cells and the lamp voltage is kept constant by means of a rheostat operated by the knob on the right, through a water-tight gland.

The instrument was calibrated on a photometer bench while immersed in water in a tank constructed of transparent acrylic sheet. It was used to measure contrast and luminance in the underwater scene, and to assess correct photographic exposure. The ratio of the luminances of adjacent white spots is 2:1, so that for the latter purpose the instrument can be directly calibrated in lens aperture numbers for average scene luminance for a given sensitive material at fixed camera speed.

(4) Regional Variations in Water Opacity

During the course of the investigations, measurements of water clarity, using the hydrophotometer, were made in various coastal regions, and interesting information was obtained.

Water nearly as clear as the purest distilled water was found in the Mediterranean, 10 miles off Malta (attenuation coefficient 1.2×10^{-2} per foot), a white disc being

visible from above the surface at a depth of 200 ft. The clarity decreased, however, as the coast was approached, and in the bays with little shipping, the attenuation coefficient was usually in the region of 3×10^{-2} per foot.

In British waters, although it is possible to find water as clear as in the bays of Malta and the French Riviera (off Plymouth and Falmouth, attenuation coefficients of 3×10^{-2} per ft. have been measured at favourable states of the weather and tide), the attenuation coefficient of the water in the Channel off a sandy shore is rarely lower than $a = 100 \times 10^{-2}$ per ft., and even in the Scottish lochs communicating with the Clyde, where the water has been claimed to be very clear, the lowest value of a measured so far has been about 20×10^{-2} per ft. In British harbour water the attenuation is very great and reaches 240×10^{-2} per ft., the underwater visibility as seen by a diver being barely one foot. This information indicates some of the regions where underwater visibility is likely to be good, but it is evident that a much wider survey of near-coastal waters would be extremely valuable. This is an oceanographic measurement problem of some importance.

(5) The Underwater Ciné-film Technique

As soon as the technical problems of working underwater with a ciné camera were solved, detailed work on visibility was carried out photographically. The decision to use a photographic assessment was arrived at partly because the photographic result was the final aim of the work, and partly because it was so much simpler to use the camera to observe underwater in a short space of time, and to analyse the results at leisure in the laboratory.

(5.1) Diving Methods

It is no part of this account to describe in detail the cameras or diving technique, but it may be of interest to mention briefly the diving equipment which enabled the setting up of lighting gear and photometry to be carried out underwater, as well as

Fig. 9. Air breathing "free" diving equipment and camera in use.

the photography. Compressed air "free diving" sets were used, the diver being quite independent of the surface and unattached in any way. The air supply (which lasts for about 30 minutes at a depth of 60 ft.) was carried on the back in two cylinders and fed through reducing and "demand" valves to a mouthpiece separated from the simple face-mask which had a flat front glass and covered the eyes and nose. A light two-piece rubber suit could be worn over diving woollens in cold water, but in the Mediterranean bathing trunks and "frogman" swim fins on the feet were the only other equipment needed apart from a weighted belt to adjust one's weight to neutral buoyancy. The diver is then free to manoeuvre up, down or sideways, with very little effort by the use of his lungs and feet.

The equipment is seen in action in Fig. 9.

(5.2) Cameras

The design of underwater cameras is discussed elsewhere together with descriptions of the cameras constructed.(1) The one used for most of this work was an electrically driven model taking 200 ft. of 35 mm. film (or just over two minutes total running time), and having the stop, focus and running controls outside the housing for operation by the diver.

(6) Visibility under Daylight Illumination

From what has already been said about the clarity of sea water, the impression will probably have been gained that seeing underwater is rather like seeing in a thick smoke fog, with visibilities at most 300 ft. This is in fact a fairly true description, except that at shallow depths the "haze top" is quite close and sunshine can give directional lighting and sparkle down to depths of 100 ft. in very clear water. The brightness of the scene is reduced by reason of the absorption in the water, but even in very turbid water, there is plenty of light for photography at depths equal to several times the limiting horizontal visibility range.

(6.1) Contrast Degradation

The visibility range is dependent mainly on the amount of light scattered in the water; this acts in two ways, firstly by forming a light background behind the object, and secondly by producing a "veiling" brightness between the object and the observer; both of these effects tend to reduce the brightness* contrast of the object, and hence its visibility. Where large masses of homogeneous water are concerned, Koschmieder's assumption(8) (that the brightness of the background to the object is independent of range) is probably applicable. The limiting range for a black object occurs when the ratio between the veiling brightness and the background brightness approaches the threshold (visual or photographic as the case may be). For a white object, however, the range will mainly be governed by the effect of attenuation which reduces the brightness of the object towards that of the background.

These limiting ranges have been calculated using Koschmieder's relations and show reasonable agreement with the trend of the photographic results.

These relations are discussed further in the appendix.

(6.2) The Photographic Method

In order to study the effects of the physical variables affecting the contrast, a flat target 4 ft. square, painted in seven neutral tones from white to black, was used, suspended from a boat in the desired location. The variables examined were range, clarity of water, reflection factor of object, angle of sunlight, and depth.

When brightness measurements had been made and the exposure determined, the

* In this general discussion on visual and photographic "visibility," the general term "brightness" is used. The terms "luminance" and "luminosity" should be understood for measured brightness and the visual sensation respectively, where the effect on the eye is being considered.
It is considered inappropriate to use these terms when discussing the photographic effect.

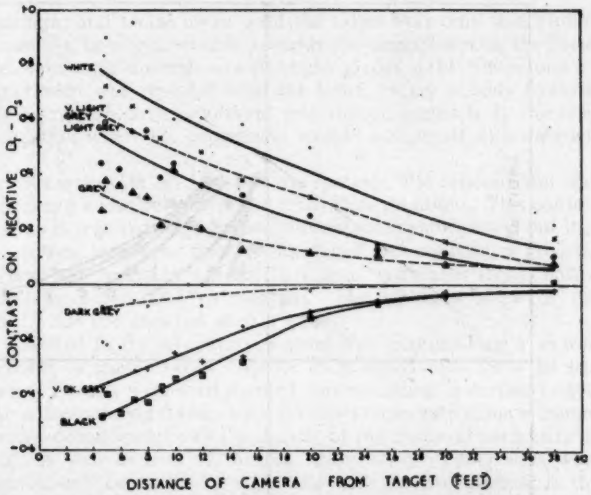
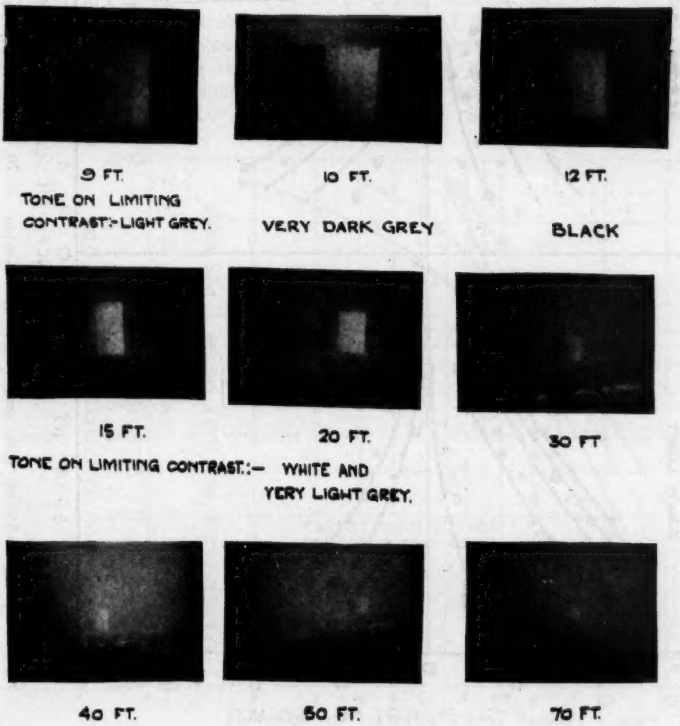


Fig. 10.—Target contrast with sea. Water transmission = 95 per cent. per half-metre (a = 0·03 per ft.); H.P.3 film; 6 ft. depth; direct sunlight.

Fig. 11 *(below)*. Appearance of grey scale target at varying ranges. Water transmission = 95 per cent. per half-metre (a = 0·03 per ft.); H.P.3 film; 40 ft. depth; down light.



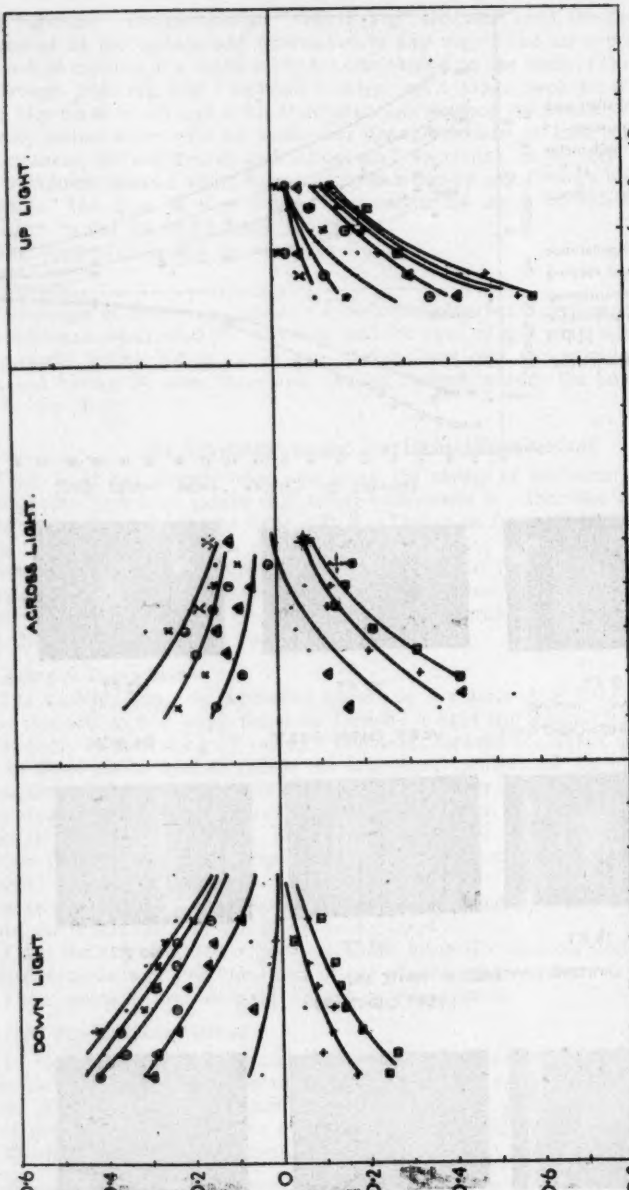


Fig. 12. Target contrast with sea. Water transmission = 70 per cent. per half-metre (a = 0·22 per ft.); H.P.3 film; 6 ft. depth; direct sunlight.

camera man took the camera, and swam away until the target was only just visible. Then, with the camera running, he swam steadily towards the target (altering the focus by means of the control operating through a water-tight gland) until within one or two feet of it. The experiment was repeated with the target facing directly towards the sun azimuth, directly away (silhouette condition) and at right angles to it; the boat then moved to another location where the experiment could be repeated with different water clarity.

As these trials were all carried out off Malta in the summer, the exposed film was sent home by air for processing under commercially controlled conditions. This control is, perhaps, not as precise as is required for accurate photographic photometry, but it is reasonably consistent when long lengths of film are developed in a continuous processing plant; development time and agitation are constant, and continuous close control is kept on the solution temperature and its strength. The resultant slope of the characteristic curve was 1.2 for the material used.

After the film was returned to the laboratory, a print was examined on a viewer, and a transparent scale made to enable target distance to be determined from the size of its image on the screen. Frames were then marked corresponding to certain target-camera distances, and the corresponding frames were cut from the negative; these frames were scanned under a micro-densitometer and the density of the image of each strip of the target was measured, as well as that of the sea background. The results were plotted as density difference, or "contrast" of each strip with the background, in the manner shown in Fig. 10. Parts of the target lighter than the sea are plotted as positive contrasts, and parts darker than the sea as negative. It will be seen that the contrasts fall from their measured value in air at zero range, sharply at first as the range is increased, and then approach zero asymptotically from either side of the axis at long ranges. The visual appearance of these contrasts is shown in Fig. 11.

The contrast-distance curves for different water clarities are similar, but at the

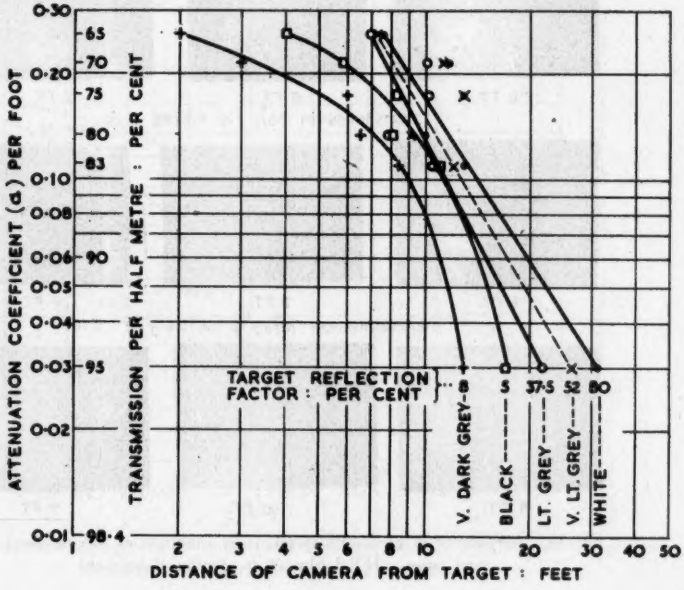


Fig. 13. Limiting ranges obtained by contrast with sea background in daylight. Limiting contrast (Density difference) = 0·2; H.P.3 film; 6 ft. depth; direct sunlight.

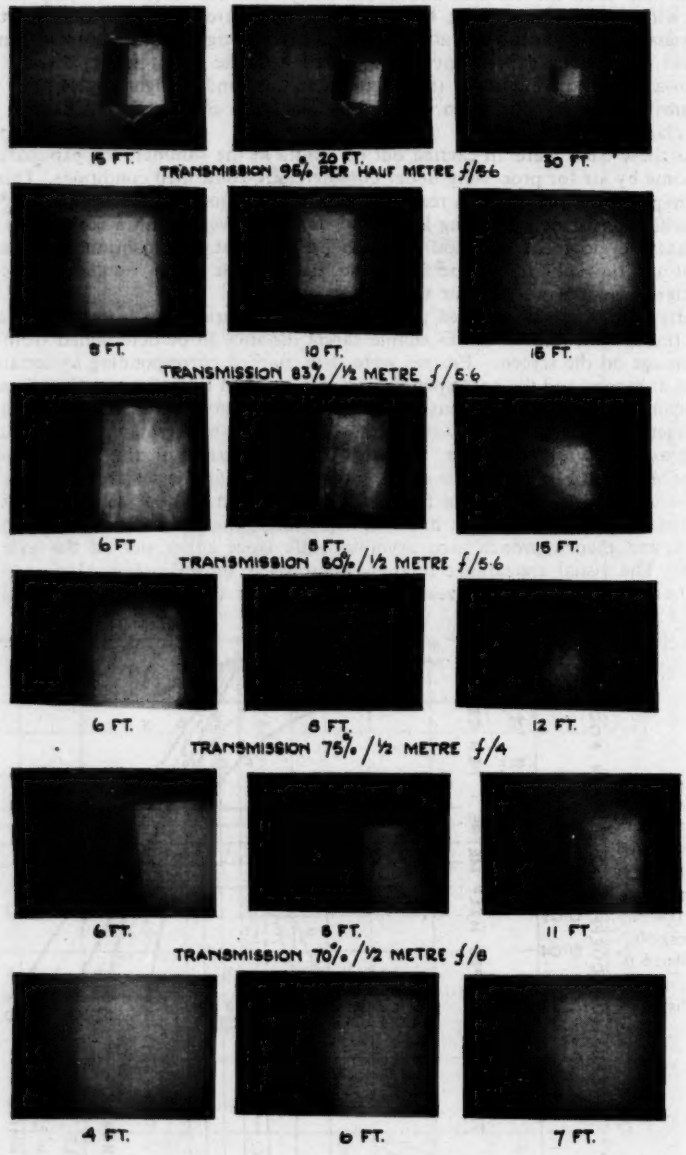


Fig. 14. Appearance of grey scale target under condition of varying water clarity and range. H.P.3 film; 6 ft. depth; down light.

higher values of attenuation the curves run together towards zero much more steeply (Fig. 12). For silhouette vision against the light, all curves drop below the axis (Fig. 12, "Up Light"), as even the white strip of the target is darker than its background, and the black strip takes on an even higher contrast, although at no time has it a higher contrast than the white strip directly illuminated by the sun. An intermediate effect results for vision "across light," the curves for only one or two of the lighter strips lying above the axis.

(6.3) Interpretation of Results

In order to interpret these contrast curves in terms of limiting range, it was necessary to fix a value for limiting contrast. This was chosen as 0.2 density difference on the negative, as being the lowest value which gave satisfactory photographic reproduction. This corresponds to a much higher brightness contrast than the value of 0.02 for the Fechner fraction normally used for limiting contrast of large areas seen by photopic vision, so that the target is always easily visible at the arbitrarily defined limiting photographic range. However, the photographic ranges determined thus are given here to show the relation between the physical variables.

Fig. 13 shows the effect of water attenuation on range of targets of different reflection factors if the above criterion of limiting contrast is applied. Fig. 14 shows the

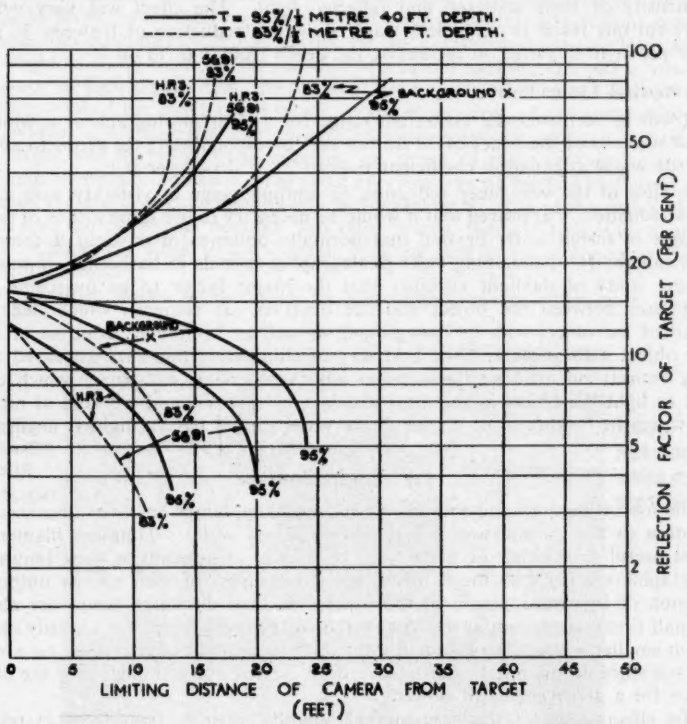


Fig. 15. Variation of limiting range of targets with reflection factor as seen by contrast with sea background for three different film emulsions.

effect photographically, and it will be seen from this that a dark-grey target has a very low contrast with the sea background at all ranges, even in very clear water, when directly illuminated by the sun. It will, therefore, be almost indistinguishable from its background at any appreciable distance at this and all higher values of water attenuation. Black targets, however, have limiting ranges approaching those of light-grey ones, but the laws connecting range with water attenuation appear to be different, although more experimental points are required before the relations can be defined with certainty.

The effect of target reflection factor is more clearly shown in Fig. 15, which also shows the results obtained with different film emulsions. The reflection factor for zero range, when the target is directly illuminated by the sun at shallow depths, is around 16 per cent., but small variations above and below this value increase the visibility range considerably, although a black object is never visible at as great a range as a white one illuminated directly by the sunlight.

When the line of sight is altered relatively to the angle of sunlight on the target, the limiting ranges can be calculated from the appropriate contrast curves, and it will be evident that as the line of sight is moved until the target is in silhouette against the bright sea background, the limiting range of the black areas will increase and that of the white areas will decrease.

Increasing the depth reduces the directional effect of the daylighting as well as the intensity of both scattered and reflected light. The effect will vary with water clarity, but one result in very clear water showed a reduction of between 30 per cent. and 40 per cent. in range on increasing the depth from 6 ft. to 40 ft.

(6.4) Physical Limitations

It will be seen that the maximum range for a clear photograph of a white object in clear water is of the order of 30 ft., but the corresponding range drops to about 7 ft. when the water attenuation coefficient rises to 25×10^{-2} per ft.

In view of the very steep reduction of limiting range of visibility with increasing water attenuation, it appeared that it would be necessary to use some means of increasing the range in turbid water beyond that normally obtained in daylight if there was to be any possibility of obtaining clear photographic records in harbours. It was evident from the study of daylight visibility that the major factor to be overcome was the veiling haze between the object and the observer (or camera), which degrades the contrast of the object with its background, as well as "internal" contrast of one part of the object with another. The best way of eliminating this haze appeared to be by relying entirely on artificial illumination with submersible equipment which could be placed to light the object in the most satisfactory manner, and working at night or at dusk, when the brightness of scatter in the water due to natural light is negligible.

(7) Light Sources

The use of mercury and sodium vapour discharge lamps has been discussed earlier, in relation to the transmission characteristics of sea water. Tungsten filament lamps are less useful than either of these types of source, as not only is their luminous and photographic efficiency so much lower, but a large part of their energy output lies in the region of low transmission of the water. Sodium discharge lamps are about one and a half times as efficient as the MA/V type of mercury lamp, but are only obtainable in much smaller wattage, so that it is difficult to judge their effectiveness on a watt-for-watt basis since no quantitative tests have been carried out, although they are obviously superior for a given generator power.

The effectiveness of the light-source radiation must be considered in relation to the photographic emulsion used. The photographic work, of which this investigation was part, was all carried out with a sensitive panchromatic emulsion. It is probable

that greater sensitivity would have been obtained with some of the sources if an orthochromatic emulsion had been used, but the panchromatic film was preferred for other reasons.

The MA/V lamp can be used with the outer glass bulb in contact with the water as can filament lamps at depths down to 100 ft. A simple bevelled rubber ring seal is used just beyond the lamp cap to seal off the lampholder, the latter being spring mounted to permit the external water to assist in increasing the sealing pressure. A well-glass is, however, required, round the sodium lamp, and likewise the "compact source" ME-type mercury vapour lamp must be enclosed in a watertight fitting or enclosure. So far fluorescent lamps have not been used for photography under water on account of the slightly more complicated circuit needed to initiate the discharge. It is conceivable, however, that use might be made of an enclosed self-contained floodlight containing several tubes for very close floodlighting or silhouette lighting, where it is desired to keep the generator power low.

Other vapour or gas discharge sources can be used for high-speed photography as discussed in Section 8 below.

(7.1) Distribution Considerations

Visibility in a scattering medium is a problem which many workers have studied. Comparison of visibility by artificial lighting under water with the visibility of targets in searchlight beams in air with high attenuation leads to definite conclusions regarding the methods and equipment suitable. Work by the authors and their colleagues[9] on the searchlight visibility relations showed that in a turbid medium ($a = 40 \times 10^{-5}$) for a given shape of light distribution, the range of limiting visibility varied approximately as the square root of the offset and inversely as the square root of the beam divergence. In other words, it increased as the amount of illuminated air between the observer and the target was decreased. The influence on range of these factors is greater as the scattering coefficient increases. The most effective way of lighting any given object under water, therefore, is by a method which illuminates as little of the water between the object and the camera as possible. In other words, the worst possible method is by use of a floodlight close to the camera, and the best is by a source as close as possible to the object.

It was further shown in the work on searchlights, where attenuation was con-

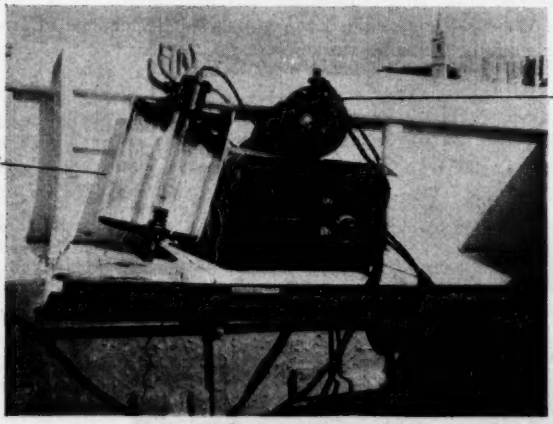


Fig. 16. Mercury vapour lamp lighting equipment with mains ballast unit.

Fig. 17. Mercury vapour lamp trough floodlights in testing tank.

sidered to be due only to scattering, that the effect on range of increasing maximum beam intensity was always very small, and became very small indeed at higher values of attenuation. It is reasonable, therefore, to conclude that the effect of the intensity of the source on the range of visibility in sea water is only slight, provided that the scene brightness is above a certain minimum value. This is a rather surprising feature, which differentiates the problem from the more usual problems in illuminating engineering which do not involve vision through a scattering medium. The minimum value of scene brightness was dictated in the present investigation by the largest available lens aperture and film sensitivity (the exposure time in the ciné camera being constant) and had, in fact, to be such that an average object of, say, 30 per cent. reflection factor had a brightness of at least 10 ft.-lamberts.

The minimum area which it would usually be necessary to light is that seen by the camera at its closest range. As the minimum distance at which the camera could be focused was 3 ft., an illumination of about 30 lm./ft.^{2} was needed over an area at least 3 ft. square, which was the area covered by the usual (short-focus) lens at this distance. The effect of candle-power on scene brightness is direct, but beyond this minimum value any increase is compensated for by change of lens aperture, and the two are essentially the same variable.

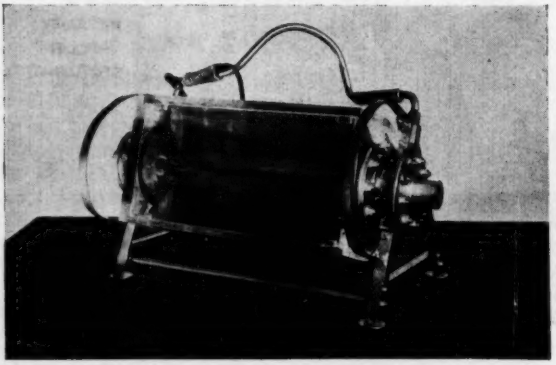


Fig. 18. Sealed trough floodlight for sodium vapour lamp.

(7.2) Experimental Work

The experimental work on artificial lighting was carried out in two stages, tank trials and sea trials.

(7.2.1) *Tank Trials*

The first stage consisted of trials in a large cylindrical diving-tank, 12 ft. in diameter, using different types of lighting equipment; photographs of a flat grey scale target were taken, mostly by a still camera through glass windows to determine the most suitable type of equipment for the purpose.

The variables in this experiment were the light-distribution characteristics and the positioning of the equipment for the given target reflection factors. As already explained, the absolute value of the intensity was not an important variable.

It was quickly confirmed that a form of close-range floodlight was the most suitable, and the experience enabled a convenient form to be designed. Two fittings were designed using 250-watt or 400-watt MA/V-type lamps, one of these is shown in Fig. 16. The reflectors were anodised aluminium troughs of elliptical cross-section, designed to light the minimum area seen by the camera from one side and about 1 ft. in front of it, as shown in Fig. 17. Tests confirmed that under these conditions sufficient light

Fig. 19. Sodium vapour and mercury vapour lamp floodlights in operation at 70 ft. depth underwater.

fell on the target even in very dirty water to fulfil the minimum requirements, while opaque screens round the lamp prevented any direct light from illuminating the water between the object and the camera outside the main beam.

A 45-watt (SO/H) sodium lamp floodlight was designed for the same task with an acrylic cylindrical well-glass to protect the lamp. The frontal area of the reflector was 14 in. wide by 8½ in. along the axis.

An experimental 140-watt sodium lamp floodlight designed by R. B. Phillips is shown in Fig. 18. It will be seen that the lamp and reflector are sealed into an acrylic housing, lamp replacement being effected through a sealed hole in the end plate.

One sodium and one mercury lamp floodlight are shown in place on the hull of a wrecked submarine in Fig. 19.

At the commencement of the work, the only existing lighting equipment with optical control was a spotlight using a 4-in.-diameter double-condenser lens, and equipped with a 250-watt ME-type mercury vapour lamp. This is shown in Fig. 16.

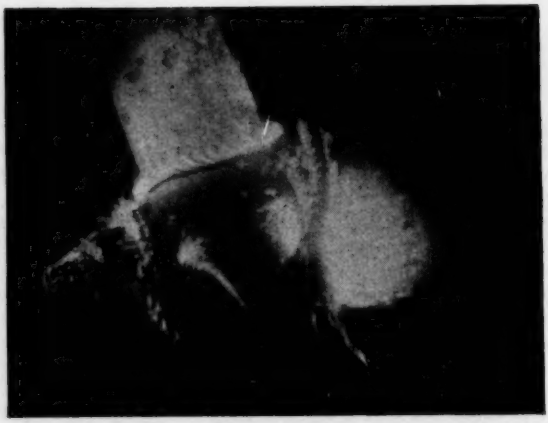


Fig. 20. Propeller fouled by rope. Photographed at night in harbour with artificial lighting.

It was made by a manufacturer of diving equipment as a powerful diver's hand-lamp, and gave a very sharply defined beam of small divergence.

As already explained, this distribution was unsuitable for general lighting purposes under water, but it was found to be a useful piece of equipment for "high-lighting" small areas, giving cross-lighting to emphasise the form of small detail. It was always necessary to use this at a large angle of offset from the line of view and in water of poor clarity it had to be very close to the target.

(7.2.2) *Sea Trials*

The second part of the experimental work on artificial lighting consisted of trials of the selected equipment in the sea. The experimental variables in the artificial lighting problem are not the same as in the work on daylighting and the same approach is not therefore relevant. As the trials were to take place in the Mediterranean, their object was rather to take the equipment designed as a result of the tank trials and discover the best techniques of using it in practice, in waters of different clarity.

The techniques found to be most satisfactory are best described by illustration of the photographic results obtained with reference to the placing of the equipment and the clarity of the water.

In the clearest water in which artificial lighting was used ($a = 6 \times 10^{-2}$/ft.) the equipment could be placed at quite a reasonable distance from the object. In more turbid water, however, the equipment must be within one or two feet of the object. Fig. 20 shows a propeller fouled by a rope, the general illumination being produced by one sodium and one mercury lamp floodlight, and the spotlight at close range picking out the details of the turns of the rope ($a = 15 \times 10^{-2}$/ft.). The situation depicted is one which is, unfortunately, frequently a matter of importance in crowded harbours, and a clear picture may save the ship going into dry dock. The result obtained with the artificial light is, of course, independent of depth of the propeller or amount of overshadowing of the hull.

In very dirty water (above $a = 20 \times 10^{-2}$/ft.) the spotlight is practically useless, and the most satisfactory method is to use the floodlights to silhouette the object or the part of the object of interest, provided that an outline view is acceptable.

Fig. 21 shows the split in the inside of a sunken floating dock in Valetta harbour. The water here was so dirty ($a = 25 \times 10^{-2}$/ft.) and the light so bad that the damage could not even be seen, and certainly not photographed by daylight alone.

This last application is perhaps the one in which there are most possibilities of

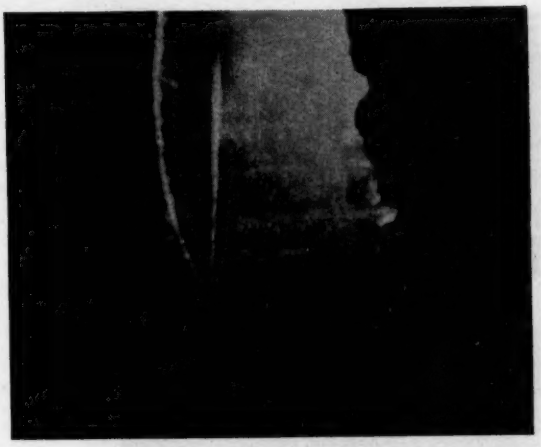


Fig.21. Split side of sunken floating dock; silhouette of fractured plate is seen at right of picture. Photographed at night in dirty harbour water with artificial lighting.

development. The more extended types of source should prove very useful for this work, and also the refractor plate lens type of floodlight as made by one manufacturer of cinema studio lighting equipment, using a 5-kw. bi-post lamp with the bulb directly in contact with the water.

(7.3) Power Supplies

In large ships with their own mains voltage generating systems, the lamps can be connected as on shore, a resistance ballast being used for the discharge mercury lamps if the supply is D.C. The sodium lamp cannot be used directly on D.C. On small ships and diving boats some form of portable supply is necessary. Three types of supply equipment were used for the lighting equipment described.

(i) A portable rotary converter was supplied with the 45-watt sodium lamp. This required an input at 24 volts from car or motor-boat batteries, and had an output of 75 watts at 230 volts, 50 cycles, which fed the stray field transformer for the lamp.

(ii) The generator supplied with the 250-watt ME mercury spotlight was driven by a single cylinder J.A.P. engine and gave 250 watts at 100 volts D.C., the lamp being fed through a ballast resistance with an inductive starting circuit.

(iii) There are many petrol generators of various sizes available, but one convenient portable plant was found to be on the "Onan" American generator, Model O.T.C.5 (B), used in the Services, with an output of 1.5 kw, 230 volts A.C. This, being able to supply up to five 250-watt lamps or 23 45-watt sodium discharge lamps, should be sufficient for most photographic lighting

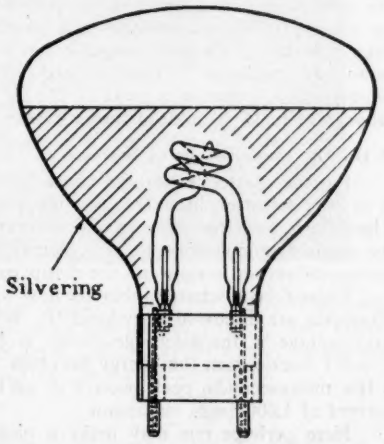


Fig. 22. Flash discharge tube, showing construction.

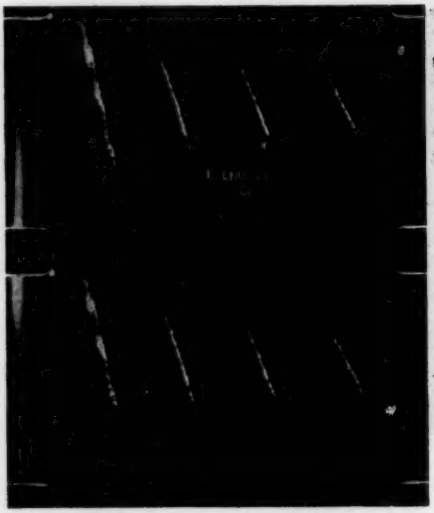


Fig. 23. Early stages in propeller tip vortex formation. Two frames from film taken at 2,000 pictures per second photoflash illumination.

work, unless it is required to photograph very large areas without moving the lighting equipment.

(8) Lighting for High-speed Photography

For the illumination of rapid events under water, the lighting problems are in many respects entirely different. Daylight does not provide enough object brightness when the camera exposure time is reduced to the values well below one millisecond necessary to "arrest" the movement of the object for a slow-motion film. Neither do any of the light sources mentioned so far permit a high enough illumination on the subject to be achieved. For continuous light systems at sea it is difficult to use powers higher than 5-10 kw. Overrun tungsten lamps or compact source mercury vapour lamps pulsed at overloads[10] can be used. The former types have been used in colour photography at depths as great as 150 ft.—the latter are a convenient source for use in laboratory tanks in hydrodynamic research.

(8.1) The Flash Discharge Source

For the shortest exposures where microsecond times are required, the only solution is to use condenser discharges through quartz or hard-glass tubes containing rare gases. These flash discharge tubes have been run under water in laboratory conditions in either the single flash condition or as repetitive light source at a high frequency. Here peak powers of several megawatts are dissipated at each flash.

These flash discharge tubes are now widely used in auxiliary studies of rapid events. Examples are discussed elsewhere[11]. When a condenser of capacitance C is charged to a voltage V, the discharge energy is $\frac{1}{2}$ CV^2 joules. At values of V = 10 kv. and C = 0.1 microfarad, the energy becomes 5 joules. Since the discharge occurs in only a few microseconds, peak powers of up to 5 megawatts may result, with a discharge current of 1,000 amps maximum.

Here perhaps one may make a plea for a far more careful and intelligent use of the flash discharge from the point of view of utilisation. A 4-joule flash when used in an adequate optical system of a "sealed-beam" type (Fig. 22) will cover a

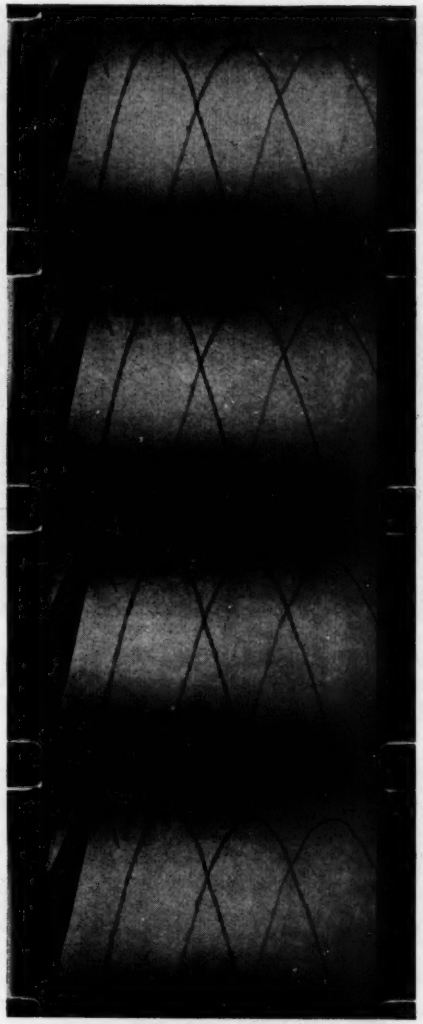


Fig. 24. Growth of propeller tip vortex cavity element. Frames from a film taken at 2,000 pictures per second; continuous illumination.

circular area under water of about 1.5 metres diameter when the source is one metre from the subject. Films can then be taken at an aperture of F/11. Too often in flash applications great efforts are made to get a high electrical energy in the flash, and the resulting light energy is then wasted by poor reflector design.

(8.2) Propeller Cavitation

One of the many important underwater phenomena requiring research is the occurrence of cavitation near the screw propeller. Due to the erosion damage of

Fig. 25. Motor-boat propeller, showing cavitation from tip of blade and boss.

the metal by this process, it is important to study the mechanism whilst this occurs in the sea itself. In the laboratory one can study in a water tunnel the vortex cavities on a model scale propeller and Fig. 23 shows the appearance of these

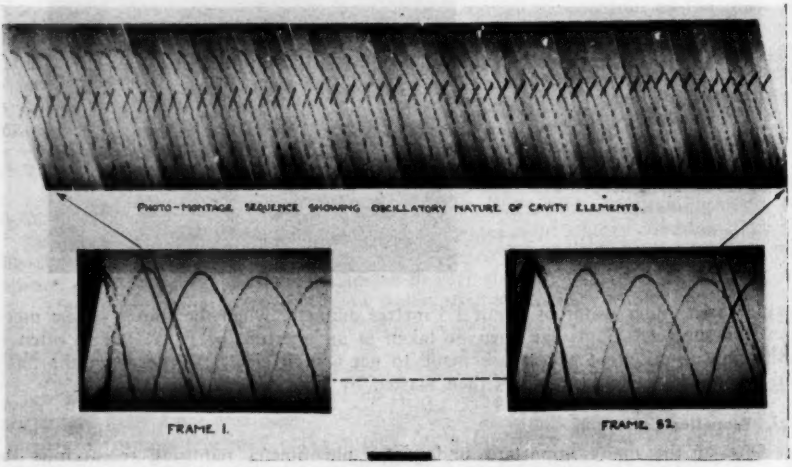


Fig. 26. Photo-montage method of propeller cavitation study.

vortices when illuminated with direct light from a sequence of "photoflash" lamps triggered successively. The pictures are filmed at 2,000 pictures/second. The fine structure of the tip vortex is studied conveniently by rear-illuminated pictures as shown in Fig. 24. In Fig. 26 a "photo-montage" system has been used to reconstruct the progress of cavity elements as they pass down the flow pattern behind the propeller blades. These exposure times are about 100 microseconds.

When individual cavities are formed in laboratory water tanks quite different illumination requirements exist, for which a flash discharge illuminant is the only solution. Here exposure times of 5 microseconds are required, at repetitive rates of about 4,000 pictures/second.

In the ocean itself the problems are more difficult, but there is no insuperable problem in using these tubes under water, and indeed these methods will be essential for the adequate study of cavitation processes in the sea. Ordinary ciné films give only an indication of the process. For instance Fig. 25 shows cavitation from the tip and central boss of a motor-boat propeller. In Fig. 26 is shown the progress of the entire vortex pattern from a model propeller in a water tunnel.

One example is the use by Fisher[12] of flash sources to study propellers of a ship under way on full scale in the sea.

There remains much research to be done in this fascinating field.

(9) Conclusions

In this paper, it has not been possible to do more than describe certain specific problems overcome, and give general guidance to any other workers in this field. As in many other aspects of illumination, the solution often has to be matched to the particular problem. Already the problems of underwater television are demanding an extension of this research.[12][13] It is felt, however, that some of the physical principles and limitations are now understood in the field of illumination under water.

The problems of visibility in air and sea water are in many respects similar: in both cases the relevant physical properties of the medium are opacity, scatter characteristics, and spectral transmission. In the present work, experimental results indicate that a similar approach to that adopted for the air visibility problem, involving the determination of contrast, is valid for the case of visibility under water.

Of the methods used for measuring the opacity of water in the sea, a submersible hydrophotometer was found to be the most suitable, and measurements which have been made with this instrument of the attenuation coefficient in various locations give an indication of the possibilities of underwater visibility.

Using a specially developed method of taking underwater films, visibility measurements of surfaces having different contrasts with their background were made photographically, under different conditions of range, water clarity, and lighting. The results are expressed in contrast-range curves, and by the adoption of a brightness contrast criterion the limiting range for photography or vision can be determined for a wide range of conditions from these data.

Artificial light sources are essential under conditions of poor natural lighting or water of poor clarity. The types of light distribution required have been established, and the correct use of equipment using mercury and sodium discharge lamps has been demonstrated.

For high-speed photography under water at picture repetition rates above 200 per second, the flash discharge source is the only solution. Study of the problems of cavitation is only one of the fields of its useful application.

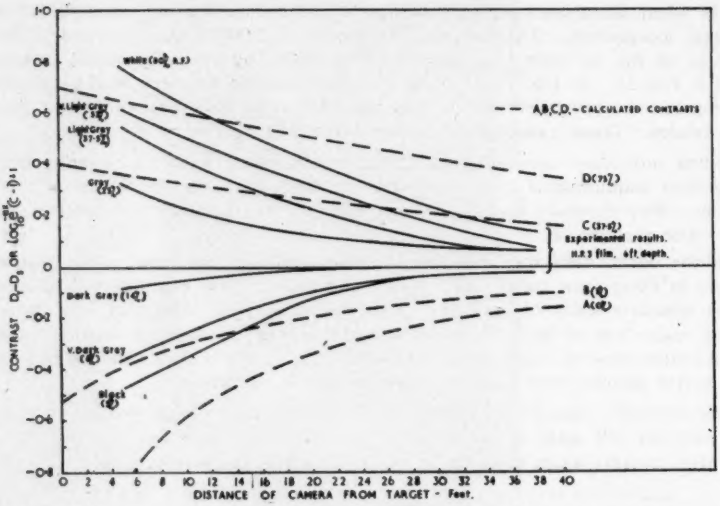


Fig. 27. Target contrast with sea. Water transmission = 95 per cent. per half-metre (a = 0·03 per ft.); direct sunlight.

Acknowledgements

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Appendix

It is interesting to compare the experimentally determined density contrast relations with those calculated assuming that the Koschmieder relation holds under water.

If it is assumed that this relation does in fact hold (i.e., the brightness of the sea background to the object is independent of the distance) the apparent brightness of the target at a range x ft. (BT_x) can be written as follows:—

$$BT_x = BT_0 e^{-ax} + b \quad \ldots\ldots(1)$$

where BT_0 = brightness of target at zero range,
a = attenuation coefficient per ft.
b = brightness of intervening medium due to scattered light.

If B is the background sea brightness at the target, then the background brightness at the range "x" is:—

$Be^{-ax} + b$ which is assumed $= B$.

Therefore, $b = B(1 - e^{-ax})$

Substituting in (1), $BT_x = BT_o\, e^{-ax} + B(1 - e^{-ax})$

Contrast of the target with its background at range x is

$$\frac{BT_x}{B} = \frac{BT_o\, e^{-ax}}{B} + (1 - e^{-ax})$$

$$\text{or } \left[1 - \frac{BT_x}{B}\right] = \left[1 - \frac{BT_o}{B}\right] e^{-ax} \qquad \ldots\ldots(2)$$

For a perfectly black object,

$BT_o = 0$, and the contrast would be given by

$$\frac{BT^x}{B} = (1 - e^{-ax})$$

Plotting this against x, the bottom curve of Fig. 27 is obtained.

The relations for targets of other reflection factor depend on the relative brightness of the target and its background at zero range, but curve A indicates the general shape to be expected.

From the observations obtained during the course of the experiment, it was found that objects of about 15 to 17 per cent. reflection factor matched the sea background when viewed down light at shallow depth. Using this observation, it is possible to calculate the contrast of objects of different reflection factor at various ranges, and the curves B, C, and D are plotted in Fig. 27 for reflection factors of 5 per cent., 37.5 per cent. and 75 per cent.

The curves (for the lighter targets particularly) are less steep than the curves of contrast on the film obtained experimentally) and which are shown for comparison purposes, but indicate within the accuracy possible under the conditions of the experiment that the results are of the form which would be expected from the theoretical relations. (The film emulsion used was developed to a "gamma" of 1.2, so that the calculated values of contrast on the film in density difference would be expected to be roughly 20 per cent. higher than actually shown.)

If a density difference of 0.2, or brightness contrast ratio of $\frac{1.6}{1}$ is taken as a limiting value for $\frac{BT_x}{B}$, this may be equated in equation (2), and if we put

$$\frac{BT_o}{B} = C,$$

we may write

$$(1-1.6) = (1-C)e^{-ax}$$

$$\text{or} \qquad e^{-ax} = \frac{0.6}{C-1}$$

Limiting range x_L is therefore given by

$$x_L = \frac{1}{a} \log_e \frac{C-1}{0.6}$$

This is a linear logarithmic relation, and if log x_L is plotted against log a as in

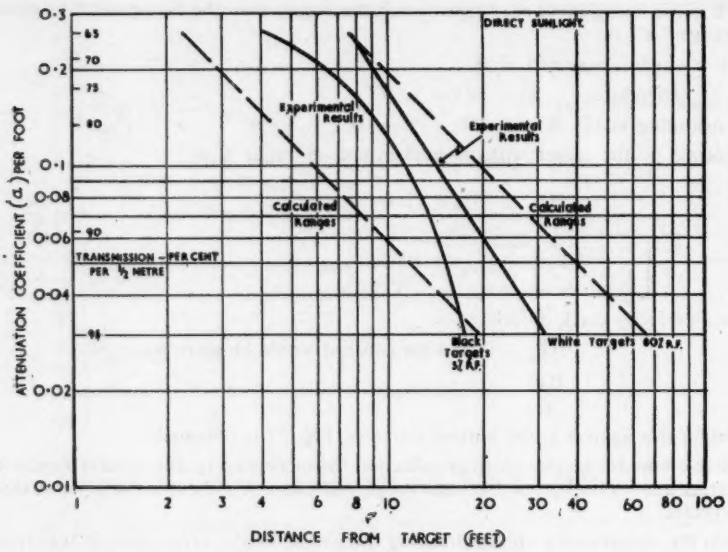

Fig. 28. Limiting ranges obtained by contrast with sea background in daylight. Limiting contrast (Density difference) = 0·02.

Fig. 28 for objects of 80 per cent. and 5 per cent. reflection factor, a linear graph results. In this figure the experimentally determined range curves for objects of 80 per cent. and 5 per cent. reflection factor are also shown for comparison.

It should again be remembered that the film emulsion to which these experimental results refer was not processed to "unity gamma."

It will be seen that the calculated ranges correspond closely to the experimental results for the black target in clear water, and for the white target in turbid water. At the opposite end of the range of water conditions for each target, the two curves diverge widely, and this may be taken as an indication that the Koschmieder relation cannot be applied too strictly to photography under water.

Discussion

DR. W. S. STILES: There are three satisfactions which I think the authors must feel—the first in having a difficult technical problem which they tackled scientifically and brought to a successful conclusion, the second in having material they were able to present to their colleagues and others in such an attractive way, and I would like to add as the third, the pleasure in "messing about in boats" in the waters of the Mediterranean.

The problem of visibility in this work is dominated by the attenuating properties of the medium—sea water. Data are quoted in the paper showing how the amount of light scattered and the amount of light truly absorbed change as the wavelength is varied. It is an interesting question how these two effects—variation of scatter and variation of true absorption—are to be weighed one against the other in deciding the best colour for an artificial illuminant, a question in which the spectral response of the receiver also comes

in. If scatter and absorption always increased and decreased together the problem would be simpler, but that seems not to be so. In a completely non-scattering medium one would presumably use light of a wavelength for which the absorption is very low and the absolute sensitivity of the recording apparatus very high. In a highly scattering medium on the other hand the absolute sensitivity of the recording apparatus is probably less important, and the best colour may turn on a compromise between low scatter and low absorption. In practice, perhaps the colour to be used is largely decided by available light sources. Could the authors add anything on this question of optimum colour?

I notice a statement that a black object is never visible at as great a range as a white object when the illumination is direct sunlight. I presume that the last qualification is necessary and that you might have a black object more visible than a white if the light were general diffused daylight. That seems to be so, in any event, for visibility in a foggy atmosphere. It has in fact been suggested that warning poles or bollards might be painted in large black and white checks to make certain of the most favourable contrast.

I will end with a suggestion which looks very much to the future: The very efficient light sources which were demonstrated to-day, giving flashes of the order of a micro-second, make one wonder whether in the future it may be possible to get round the difficulty of scattered light by a technique somewhat resembling radar technique, a pulse of light being sent out from the source and a reflected pulse from the object coming in to the camera. If the pulses are of sufficiently brief duration, scattered light pulses will not arrive at the camera at the same time as the pulse you are trying to record. I estimate that with a pulse of a micro-second in water a light will travel several hundred feet; if you could have a hundreth of a micro-second flash —obtained perhaps with a shutter—and also have a delayed shutter on the camera which prevented one obtaining any record over an interval appreciably longer than the flash, you would have a system which in theory would greatly reduce the scattered light in your photograph. This is looking far ahead but I would like to know whether the authors have any comments on this subject.

MR. J. S. SMYTHE: I myself have never been engaged on work underwater, but during the war was associated with a considerable programme of investigation on the properties of the atmosphere; it has been most interesting to compare the technique and problems of these two investigations.

In 1939, little was known about the properties of the atmosphere which control visibility in the air and from ground to air, and the expectation of air attacks naturally made the problem of first importance. Early full scale experiments only showed that without a knowledge of the factors concerned, little systematic information could be expected. We, therefore, had recourse to model experiments, using a tank in which the water was made turbid by the addition of a small quantity of disinfectant; thus in this work, the conditions were very similar to those described by the authors, and the conclusions on the use of aircraft flares—for example, the effect of light illuminating the haze between observer and object—were analogous to these for underwater illumination at full scale.

The mechanics of transmission in the air and underwater seem to be strictly comparable; the main difference is that in the air attenuation coefficients are much lower, and thus measurements must take place over a long range, introducing all the problems of working between two distant stations, in one of which, the aircraft, the observers suffer extremes of discomfort and inconvenience. Another factor which modifies the air technique is the relatively small amount of attenuation due to absorption, except in heavy industrial haze. Since attenuation due to scattering is preponderant, it is

possible to calculate the transmission from measurements of the scatter index made at one point; unfortunately, this is useful only if the atmosphere is reasonably uniform over the whole range involved, which is seldom true. It would be interesting to know whether the authors have had any difficulties due to variations in the turbidity of water.

This comparison has raised in my mind some specific queries on which I should like the authors' guidance. Firstly, in the air no correlation was found between the relative magnitudes of the scatter coefficient and the absorption coefficient; an increase in one did not result in a corresponding increase or decrease in the other. Have the authors found this to be so under water? Secondly, the shapes of the scatter distribution curves given in the paper for three very different water samples show little variation. It would be interesting to know whether this is generally so, since in the air very wide variations occur. Thirdly, it has been suggested that in addition to attenuation by scatter and absorption, there is a third effect of turbid media, namely, a loss of definition due to blurring of outlines. I believe that this has been proved non-existent, and the authors' views would be valuable.

With regard to the equipment used I should be interested to know whether there are any circumstances in which it might be easier to exclude water from the lighting equipment by pressurising through a pipe, rather than by making the equipment watertight.

DR. J. N. ALDINGTON: I welcome the opportunity of saying a brief general word about this work because I believe, as some of you know, that the Society does benefit when we can get pioneer workers to come to a meeting and present their work to us in a way that all can understand. We have had that happy combination this morning—we have had work which has taken many years to fructify described to us in a way which I know has delighted the ladies of our party just as much as it has delighted and instructed us.

I am really stepping in before Mr. Chesterman has an opportunity of saying anything in relation to Dr. Stiles's concluding remarks. Mr. Chesterman is a very persuasive person and I think following Dr. Stiles's remarks he is going to ask that flash sources shall now be produced capable of a total flash duration of only about 1 per cent. of the minimum at present attainable, the duration of which is imposed by the very nature of matter itself—and if I know anything of Mr. Chesterman he will expect a solution.

MR. J. M. WALDRAM: During the war I came across the saying that there are very few men of sufficient stature to have their head in the air and their feet on the ground at the same time. Mr. Chesterman and Mr. Collins are unique in being able to have their feet on the bottom of the sea and yet to be able to come up for air, bringing with them such fascinating pictures and such lucid descriptions that we are all filled with admiration for the work they have done.

Mr. Smyth has already drawn attention to some of the technical features, particularly to the fact that during the war we did something in the air rather similar to what Mr. Chesterman is doing under the sea. I wonder whether he was able to make any measurements himself of the polar scatter index of the water he was using. In conjunction with our atmospheric work we measured the polar scatter coefficient of water and obtained curves which were similar to those which were obtained in the lower levels of the atmosphere. Fig. 2 of the paper, which gives the typical polar scatter index of water, might have come straight from one of the series that we took in the air near the ground. In this part of the atmosphere the polar scatter index curve is of nearly constant shape, a fact which enabled apparatus to be devised, by Mr. Collins, in which the polar scatter index of air was measured at a fixed angle and

the total attenuation derived from it. One wonders whether there is any parallel in the mechanism of scatter in the water.

The shape of the polar scatter index curves is not characteristic of molecular scatter, only scatter from much larger particles. Have the authors any information as to what is the mechanism of scatter in the water?

We have had some experience of problems of underwater photography, in experimental tanks during the war. I recall a very large tank which one of the service departments built, which was as big as a large auditorium, but it was designed without very much consideration of the photographic and optical problems involved. One of the interesting characteristics of the high attenuation coefficient of water is that there is a physical limit to the size of such a tank, for a given method of lighting. If that tank had been built any bigger they could not have taken any photographs in it at all, even in the clearest water.

One other point which I should like to make concerns the visual range of a white object as compared with that of a black object. A white object with the sun on it can be seen, in some circumstances, at ranges somewhat greater than the maximum at which a black object can be seen. A colleague of mine has seen a sunlit, white, snow-covered mountain in clear air at ranges exceeding the maximum range at which you can see a black object in the atmosphere without any scatter from aerosols at all. The reason is that a black object cannot be blacker than black, but if a white object is illuminated there is no limit to the brightness which can be obtained.

DR. R. C. G. WILLIAMS: In presenting this most interesting paper on underwater illumination, I think that Mr. Chesterman and Mr. Collins have been rather over-modest in outlining the applications of the important new technique of underwater vision. The interest of the public was, undoubtedly, roused over the use of underwater television for the location and identification of the sunken submarine Affray, but there are, of course, many other uses. It requires little imagination to visualise the application of this technique to locating various aggressive objects that might harass our sea lanes in the event of war, while for more peaceful application it is a valuable research tool in the field of marine biology. What has become popularly known as "sea farming" may provide some solution to the problem of feeding the future world population, and I understand that a marine biological institution in Scotland is already carrying out research work in this field.

The difficulties inherent in seeing under water are well summarised by the figures quoted in the paper of visibility in clear air of 100 miles dropping to 355 ft. in distilled water and to a foot or so in harbour water. The instrument used for viewing —whether a photographic camera or a television camera—has certain technical advantages over the human eye, but the underwater illumination of the object to be viewed gives probably the greater scope for development, particularly when allied to the possibilities inherent in the television technique of a wavelength sensitivity extending well into both the ultra-violet and the infra-red, and the linearity of the photo-electric effect at low levels.

The choice of a suitable wavelength for illumination quickly leads to the dilemma that the longer wavelengths have a much higher attenuation in this very dense medium, while the shorter wavelengths provide serious scatter effects. In Fig. 3, where measurements of this effect are plotted, I think it a pity that the energy output of the sodium vapour lamp could not also have been superimposed in view of the value of this source of illumination in denser waters.

In conclusion, I felt that the stimulating suggestions made by Dr. Stiles in his earlier contribution to the discussion may not be so remote as he pictured, particularly

in view of the very wide range of wavelengths to which some of the latest pick-up devices are responsive.

DR. H. H. BALLIN: I was surprised to hear reference in the paper to the fact that fluorescent lamps were not considered because of difficulties concerned with the circuit. I should have thought that the fluorescent lamp circuit is very much more favourable than the circuits of other discharge lamps, but that perhaps their shape is not so suitable.

Open type fluorescent floodlights fitted with waterproof holders have been successfully used under water, but perhaps pressure would be too great at the depths at which the authors have to operate, and further, such a light and rather long fitting might be more difficult to handle.

A few years ago I saw a French film taken under water in beautiful colour and I am wondering whether the authors could say from their experience whether this colour effect was overdone or whether different conditions obtained.

The authors reply to the discussion as follows:—

MR. COLLINS: Several people have drawn attention to the close parallel between work on visibility in the air and the work in water. When we started this work, we ourselves felt that the two problems were analogous and we proceeded on that assumption.

We should have liked to duplicate the instruments used in the air, for had we been able either to measure the scattering or taken the polar scatter distribution curve we could have obtained a great deal of useful information. Unfortunately this was not possible and we had to base our work on existing information. We both feel that this is an important piece of research which has still to be done, and if it is decided to go any further with this work it will probably be necessary to do these measurements on polar scatter and the relation between scatter and attenuation actually in the sea.

We were always concerned with very much shorter ranges under water than those used in the air investigations and we found that we were not troubled with changes in the turbidity of the water over the range in which we were interested. The instrument we used measures transmission over half a metre of water which is essentially transmission at a given point. The instrument can be moved to measure at any level required, but except very near the bottom we did not find very great changes.

The analogy with air suggests that Dr. Stiles's remarks are correct, and that we should probably find under completely diffused light that a black object could be seen at a greater distance than a white one. Our work, however, was all done in the sunlight of the Mediterranean because we were particularly concerned with the directional effect, so that we have no data where directional lighting is not playing a great part.

With regard to the selection of light sources, I think this is a matter of choice of the practical lamps available. We felt at the time that there were really three choices open to us—tungsten lamp, mercury vapour lamp and the sodium discharge lamp. The choice was considered on the light of the total attenuation curves of the water, and, as several people have pointed out, Fig. 3 shows that the transmission falls at the short wavelength end of the spectrum due to scattering and at the other end due to absorption. We chose the mercury vapour lamp as giving, particularly in clear water, most of its energy where there was high transmission, and the sodium lamp which gives its energy in a region of high transmission particularly in less clear water. The decision not to use the fluorescent lamp was, I think, based on the practical ground that its use would involve more cables. As a light source it would be useful, particularly in silhouette work where you are trying to outline a break in a plate and where you could light a large area by putting a fluorescent lamp behind the surface. With regard to pressurising, again we felt that this was rather a complication. We have, however,

used pressurised cameras; these incorporate a small self-contained compressed air supply ment, to avoid constructing a heavy casing. In harbours where a compressed air supply would be available you do not usually work at great depths and it is not difficult to seal your lighting equipment. So far this has been the simpler course, but it might be advantageous to pressurise it for working at greater depths.

On the subject of the mechanism of scatter in the water, from the curves of Fig. 2 we deduced that the scatter is from particles which are present in a large range of sizes. In clear water where the colour of the scattered light is blue, it would seem that mainly small particle (probably molecular) scattering is involved, and here some workers have found that a light yellow filter improves contrast in a photograph. We were mainly concerned, however, with trying to improve visibility in more turbid water, where the scattering seems to be from much larger particles and is non-selective; here we found no appreciable benefit in using yellow or orange filters over the camera lens. The particles do not ever seem large enough to destroy the definition of a sharp edge, although the contrast may often be reduced by light scattered from adjacent paths on either side of the edge.

I think the film referred to by Dr. Ballin was probably one made by J. Y. Cousteau, using a colour film available on the Continent, which reproduces very beautifully the wonderful colour effects in the Mediterranean.

MR. CHESTERMAN: I think the idea based on the radar system is very interesting and one which ought to be studied further. The problem of getting to this exposure level is extremely difficult, though it can be done with a Kerr cell, but this is a very tricky operation and it would be a major research to tackle it. We are working on the related problem of trying to reduce the time of flash of the xenon discharge source.

Another interesting point which has been raised is the problem of a harvest from the sea. There has been a very interesting analysis made of the possibility of getting a high protein yield by underwater harvesting of clams, and I think it was an American who worked out that the yield per unit area was about six times as much under the sea as could be obtained in a field.

The oceanographic applications are extremely important and are already under consideration at the National Institute of Oceanography.

Television, of course, is only just beginning. The television camera has the enormous advantage of being able to go to great depths and stay there as long as desired.

It will, perhaps, interest you to know that the first underwater television camera in this country was made by three of our colleagues at the Admiralty Research Laboratory using a standard camera unit[14] which had been previously ordered for laboratory investigation. Delivery of this unit was expedited and an improvised underwater casing rapidly made, the installation in H.M.S. Reclaim being completed within three weeks to assist in the identification of wrecks located by accoustic means. The success in identifying the wreck of the Affray is well-known history.

Photography of the screen of a television monitor tube at the surface is a valuable method of taking underwater pictures at a great depth.

Ref.:[14] Anon. *The Engineer* **193**, 642 (1952)

Additions to List of Members

The following applicants have been duly elected by the Council to membership in the Society, and their names have been added to the list of members:—

CORPORATE MEMBERS:—

Atherton, T. ..... Dorman and Smith, Ltd., Ordsal Electrical Works, MANCHESTER.
Bayliffe, C. S. ..... 21, South Hill Street, Oldham, LANCS.
Burslem, H. ..... 17, St. Edmonds Road, Bootle, LIVERPOOL, 20.
Cooke, T. S. ..... 4, Belfort Road, Gateacre, LIVERPOOL.
Gerber, G. ..... 2, Valda Str. Ext., Townsview, Johannesburg, S. AFRICA.
Heath, B. G. ..... 201, Pasteur Gardens, LONDON, N.18.
Jones, C. V. ..... 39, West View Drive, Woodford Green, ESSEX.
Jury, D. H. H. ..... 93, Ashmore Grove, Welling, KENT.
Kumar, B ..... c/o Basant Pran and Co., 9, Old Court House Street, CALCUTTA.
Mehta, S. F. ..... Sleater House, No. 1 Sleater Road, Bombay, 7, INDIA.
McLeod, D. ..... 341, Easter Road, EDINBURGH, 6.
Murthy, B. K. N. ..... 21, B.I.T. Three Room Block, Matunga Road, Bombay, INDIA.
Nicholls, T. A. ..... 2, Stapylton Avenue, Harbourne, BIRMINGHAM.
Price, S. E. ..... 25, Oakfield Grove, Clifton, BRISTOL, 8.
Reid, R. W. ..... c/o Lever Bros. (S.A. Pty.), Ltd., P.O. Box 909, Durban, S. AFRICA.
Sergant, Miss G. A. ..... The Helen Graham House, Gt. Russell Street, LONDON, W.C.1.
Simpson, L. ..... 98, Wellgate, Rotherham, YORKSHIRE.
Skinner, J. B. ..... 51, Harley Shute Road, St. Leonards-on-Sea, SUSSEX.
Stanton, L. ..... 50, Stechford Lane, Ward End, BIRMINGHAM, 8.
Young, W. ..... 136, St. James Road, Bermondsey, LONDON, S.E.16.

COUNTRY MEMBERS:—

Carter, T. J. ..... c/o Wilson Sons and Co., Ltd., Rua de Paranapiacaba, 64, Caixa Postal 523, Sao Paulo, BRAZIL.
de Freitas, J. O. ..... Av. Angelica, 955, Sao Paulo, BRAZIL.
Thrupp, W. F. ..... c/o Dept. Works and Housing, 225, Bourke Street, Melbourne, Victoria, AUSTRALIA.

STUDENT MEMBERS:—

Cook, P. ..... 40, Lionel Road, Canton, CARDIFF.

TRANSFERRED TO CORPORATE MEMBERSHIP:—

Hollingworth, E. ..... 15, Roseville Terrace, Manston, nr. Crossgates, LEEDS.
Powell, C. R. ..... Exterior Lighting Dept., General Electric Co., Ltd., Magnet House, Kingsway, LONDON, W.C.2.

Register of Lighting Engineers

The Council have accepted the following applications for inclusion on the Register of Lighting Engineers:—

L. S. Hyatt, P. G. Goulding, D. McPherson.

Comfortable Lighting—Its Study and Realization

By L. C. KALFF, C.E., Arch.B.N.A.

In the first place I should like to thank the Illuminating Engineering Society for inviting me to come and speak at this meeting. It is an honour for which I am very grateful. It also means that the work we have been doing in Holland and the results of our investigations have interested you, and we are eager to submit our theories to your competent criticism—which is the best way to obtain reliable results.

Five years of black-out gave Holland a great craving for more light. Fluorescent lamps with their high light output had hardly been available before the war, but they now appeared in the market. Consequently since 1945 there has been a very rapid development in lighting technique and lighting levels. We believe that the lighting standards in Holland are among the best on the Continent, especially in private enterprises, industries, banks, offices, stores and shops, and in public lighting. On the other hand, the lighting standards of official buildings, such as schools, hospitals and government buildings lag behind those of some other countries.

I would like at this stage to pay a tribute to one of the most eminent men in the lighting field—Ward Harrison, of Cleveland, U.S.A. He made that remarkable contribution to the American I.E.S. Transactions in 1937 called, "What is wrong with our 50 ft.c. installations?" It is true that he could not give a satisfactory answer to this question, but there was great merit in raising the problem. He is perhaps largely responsible for the investigations we have now started. As Harrison pointed out, new lighting standards call for new principles and new design, since the old methods no longer give good results or a satisfactory atmosphere.

Up till 1910-1920 it was usual to have in our houses rather dark walls and ceilings. Artificial lighting was limited in comparison to what we have now and for that reason could only be used as local lighting. A lamp over the table, a reading lamp, or wall brackets near the fireplace could only spread small circles of light.

Gradually the output of electric lamps grew. Electric current prices went down and light became cheaper. From 1915-1925 the first general lighting systems appeared. It is true that the then usual levels of illumination (4 to 6 lm./ft.^{2}) would now be considered much too low. In those days the tendency to use white ceilings and light colours for walls and furniture began. This trend had been advocated by decorators and was warmly supported by lighting men who stressed the point of efficiency. Gradually this vogue to have light colours in interiors became more and more general in Europe and in America. When Harrison wrote the above-mentioned article, these high level installations (50 lm./ft.^{2}) did not give satisfactory results in these light-coloured interiors. We believe that the theories I shall discuss explain why this was so, and I hope to show not only that high level installations call for careful distribution of the light so that inessential things do not appear too bright, but also that this careful planning of brightness demands closer co-operation with the decorator, because we will have to go back to darker-coloured walls and ceilings if we are to obtain comfort and atmosphere similar to what we had before under the lower level installations.

Seeing is an essential human activity and arouses individual sensations in every man or woman. We would like to make these sensations as pleasant as possible but you will agree with me that arousing pleasant sensations is not the first and only task of the physicist or the technician. Certainly the scientists and technicians who have

The author is with N.V. Philips, Gloeilampenfabrieken, Eindhoven, Holland. Address presented at a meeting of the Society held at Eastbourne, May 22, 1952.

been experimenting in the lighting field for the last 30 years have contributed a great deal to our knowledge of lighting as a means of making things visible. They have found laws and rules, methods of calculation, limits and threshold values to avoid discomfort, and from their work have come a considerable number of formulae, calculation methods and measuring instruments which are very useful to the lighting men, but which, unfortunately, are usually clumsy tools in the hands of the creative artist, architect and decorator.

Until now co-operation between these two groups has been almost a one-way traffic—lighting men trying to induce the artist to include light in his decorations which will give a certain illumination and avoid discomfort from glare, shadows or reflections. The artist has been reluctant to accept these ideas partly because he did not like to complicate his work further and partly because he felt the tools given to him by the lighting expert were inadequate for his purpose.

For the architects, and really for everybody, the calculations of brightness and brightness ratios and also of glare are of very limited value, since these calculations can only be made *after* the conception of an interior. In the activity of the creative artist they can only be controls and give no guide to the direction in which he should think. We believe that this is also a reason why the competence of the lighting expert is often regarded with some distrust.

I believe the creative artist to be right. As long as we can only give him the ways and means to obtain lighting of a certain level without discomfort, he has the right to consider the lighting problem an uninteresting one. Only when he feels that he can handle light in the same way as he can handle colours, shapes and materials will he feel able to master the problems that by then will have become part of his activities. For that reason it is necessary for the lighting expert to take a completely different attitude towards the study of lighting. He must try to understand the problems of the artist, and it is for this reason that we have tried to find a new approach towards these problems.

You will find in this address more often the expression "we believe" than "we know"! As a matter of fact very many things I suggest here are difficult to prove in the sense that we can prove a mathematical or physical law. For instance, our reasoning starts from the assumption that the human activity of seeing has not changed through the ages, and that our habits and requirements in relation to seeing under artificial light are the same as those under daylight conditions, which have always been the same.

If we look at an object our visual field is filled by a picture. The visual field itself is limited by a solid angle of a peculiar shape, outlined by the contours of our eyebrows, cheeks and nose. This solid angle can be divided into three parts:—

(i) The visual task.
(ii) The immediate surroundings.
(iii) The background.

We adopted the following method to determine the size of these three parts.

(i) The task lies within the solid angle inside which we look closely at an object, moving both eyes from left to right and up and down, without moving the head. Such an angle is given approximately by an open book of normal size, seen from a normal distance. We have found that all the objects which we examine with the eyes moving and with the head kept still are included in a cone with an apex angle measuring 2 x 10 deg. laterally and 2 x 8 deg. vertically.

(ii) The angle of the immediate surroundings has been found by observing objects or surfaces of a larger size, looking at these objects with both head and eyes fixed. If we want, for instance, to get a first impression

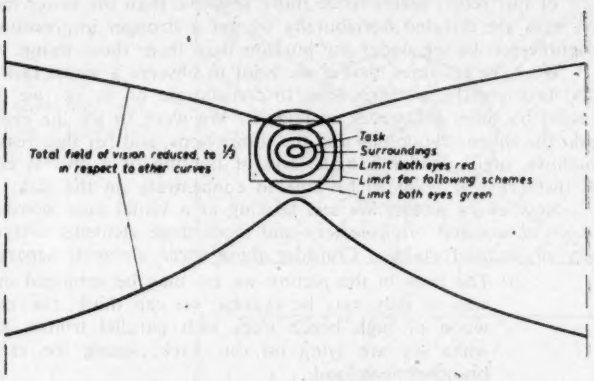

Fig. 1. General scheme of visual field.

of a picture, the average observer involuntarily chooses a distance from this picture of about 2.5 times the width of the picture or 3.2 times the height of the picture. This gives a solid angle of 22 deg. to right and left and 17.5 deg. up and down.

(iii) The rest of the visual field we may call the background. The greatest importance is attached to the task and the least to the background.

We can project the outlines of these three elements of the visual field on a plane (Figs. 1 and 2) and we can also project on the same plane the different parts of our retina through the focus of our eye-lenses. Our retinae are not homogeneous in construction and sensitivity. The most sensitive part is the yellow fovea, which we use to see the smallest details of the visual task, then we have the area where cones and rods permit us to see colours and brightness, and outside that part of the retina are the rods which detect only differences in brightness.

It is a striking coincidence that the limits outside which we do not perceive red and green as colours are just outside the limit we have accepted for our immediate surroundings. Outside these limits for colour sensitivity we do not see details and we cannot distinguish colours. We may, therefore, assume that the background is of relatively small importance in comfortable seeing. We only know that vivid brightness-contrasts and movements can easily be registered from these angles, but that we have to turn our head in order to see what really is the cause of this distraction.

There is another interesting detail in the construction of our eyes. The upper

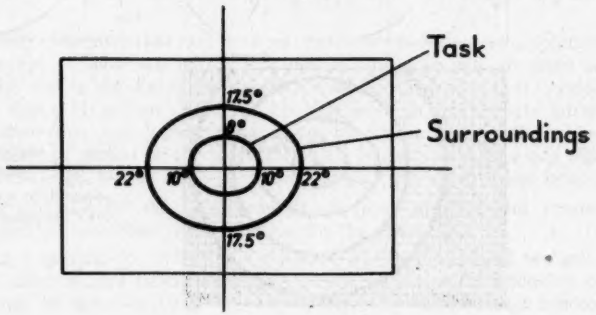

Fig. 2. Region of visual field of main interest when looking at an object.

half of our retina seems to be more sensitive than the lower half. This means that if our eyes are directed horizontally we get a stronger impression from the colours and brightnesses we see under the horizon than from those things we see over it.

We have reasoned that if we want to observe a visual task in comfort, i.e., to see that task clearly, we also want to concentrate on it, i.e., we do not want to be distracted by other influences around it. We want to see the essential characters of the task, the shape, the colour and the dimensions, and for that reason we sometimes want shadows, highlights or a high level of lighting or a special colour of light. But in all instances we want to be able to concentrate on the task.

Now every picture we see, looking at a visual task, consists of three elements—*lines, colours* and *brightnesses*—and these three elements determine whether vision is easy or uncomfortable. Consider these three elements separately:—

(i) The lines in the picture we see may be arranged in a rhythmic and quiet way or they may be chaotic; we can think, for instance, of looking at a wood of high beech trees with parallel trunks, and then looking at it when we are lying on our back, seeing the criss-cross design of the branches overhead.

The lines in a picture can concentrate our attention on the task, either by pointing towards it or by being arranged concentrically around it. If there are many lines that have not been so arranged and have no relation whatever to the seeing task, they will not help to concentrate our attention on what we want to observe.

(ii) We can divide the colours into two groups: (a) the warm ones from yellow through orange to red, purple and brown, and (b) the cold ones, yellowish-green to green, blue, violet, grey and black.

The warm colours seem to be most attractive. They also seem to many of us to be nearer than the cold ones. For that reason we think the cold colours are more adequate for the background, whilst we should like to concentrate the warm colours on the surroundings and the visual task. In practice we unconsciously very often do so. An actress or a

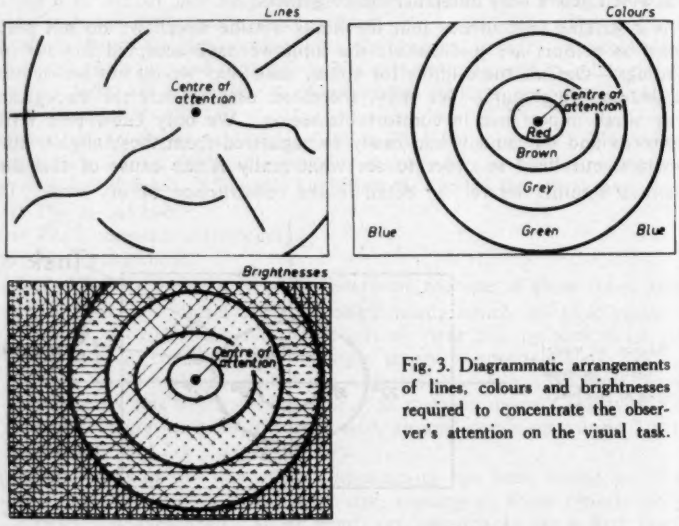

Fig. 3. Diagrammatic arrangements of lines, colours and brightnesses required to concentrate the observer's attention on the visual task.

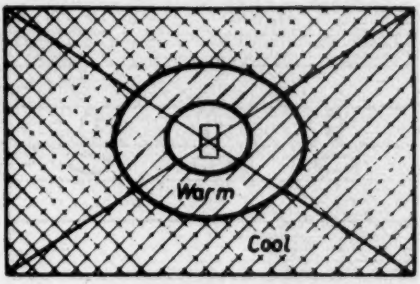

Fig. 4. Composition of scheme with lines, colours and brightnesses designed to concentrate attention on single task (reading).

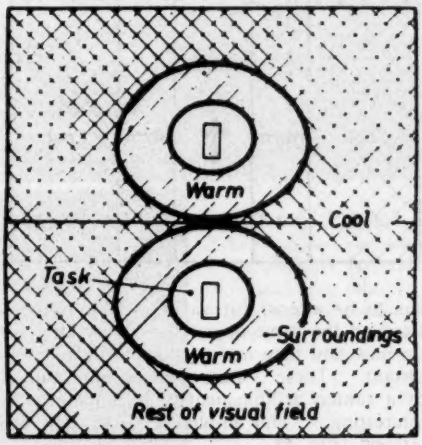

Fig. 5. Scheme designed with two centres of interest, one for reading and the other for resting the eyes.

singer in a theatre will prefer to appear in a bright and warm-coloured dress against a cool background. One can hardly imagine an artist on the platform in a grey or blue dress against a bright red or orange screen. If we want to decorate the centre of a room by putting flowers on the table we do not obtain the same results from blue flowers in a vase on a red tablecloth as we do from red, orange or yellow flowers on a green cloth.

(iii) It is generally accepted that the area of greatest brightness in a picture catches the eye. There are many examples of this—we put an artist in the limelight, we lay the dining-table with a white cloth, the bride is dressed in a white dress, Napoleon chose for his battles to sit on a white horse, etc. It is therefore only logical, if we want to concentrate on the visual task, that this task should be the brightest object in the visual field and that the surroundings should be less bright and the background still less bright.

Fig. 3 shows diagrammatically the arrangements of lines, colours and brightnesses required to concentrate the observer's attention on the visual task.

If we now compose a scheme for these three elements in the visual field, we get a picture in which lines, colours and brightnesses co-operate to keep the attention of the observer concentrated on the task (Fig. 4). Of course, this fundamental scheme

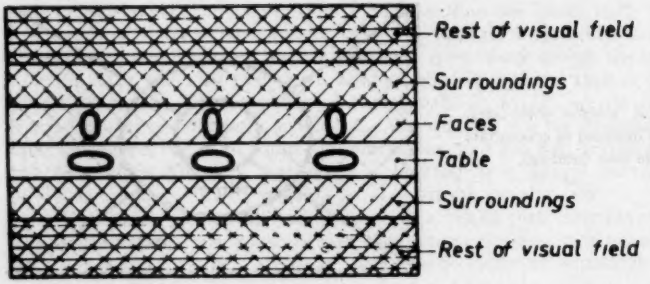

Fig. 6. Scheme of lines, colours and brightnesses for a restaurant.

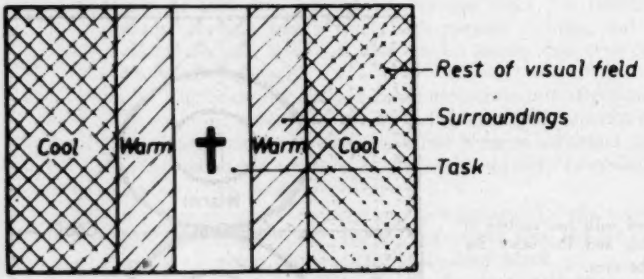

Fig. 7. Scheme of lines, colours and brightnesses for a church.

has to be altered for various circumstances. In general we do not keep our eyes fixed on the same object for a very long time; even when writing or reading we look up now and then and we like to fix our eyes on other things which are a little more distant. These objects then become another seeing task which should be surrounded by a similar arrangement of lines, colours and brightnesses, in order to be sufficiently interesting. This implies a decoration scheme in which there are two centres of interest (Fig. 5).

For rooms in which people sit looking in different directions, like dining-rooms and board rooms, the scheme has to be altered into horizontal zones of different brightness and colour. For instance, in a restaurant the zones of interest in which the seeing tasks can be found are the dining table and the faces of other guests. Over and under these zones, which should be brightest and in the warmest colours, the brightness and the warmth of the colours should diminish (Fig. 6). For such rooms it will be best to keep the ceiling rather dark, either by keeping the light away from it or by giving it a dark colour. Indirect lighting in a restaurant destroys all atmosphere and takes away the attention from the essential things in the room. In a church we are inclined to look upwards. There we may speak of vertical zones, the central one of which has to be brightest and warmest in colour, whilst gradually the zones further away from the centre should become darker and cooler (Fig. 7).

It must be understood that what we are doing here is not endeavouring to give recipes for artistic effects, but we think that these schemes respond to the way man is seeing and reacting subconsciously to the lines, colours and brightnesses he takes in through the eyes.

We think that these line-colour-brightness schemes will bring practical results. They are simple and are understood both by the lighting expert and by the artist. They are sufficiently vague to give the creative man complete freedom, and yet they will convince him of the fact that " light is part of the picture " and so part of his activity.

Fig. 8. *(Above).* 'Landscape' by Rousseau illustrating the instinctive use by the artist of lines, colour and brightness to concentrate attention on the centre of interest.

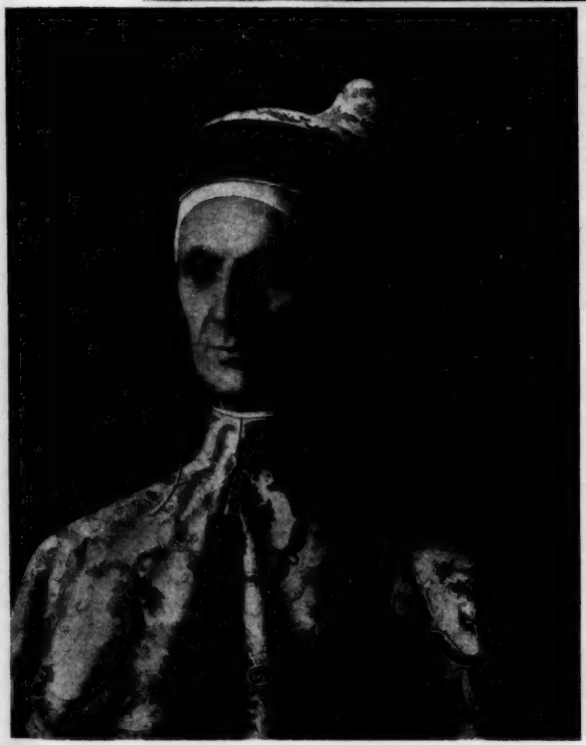

Fig. 9. 'The Doge of Venice' by Bellini. The centre of attention is the warm-coloured face with the strong contrasts of the dark eyes. The lines of the collar and hat are arranged concentrically around it, the lines of the shoulders point towards it, and the bluish-green background is cool and diminishes in brightness near the frame.

Fig. 10. Test booth in demonstration laboratory.

Figs. 11 and 12 *(Below)*. Effect of changing brightness ratios by changing the lighting scheme

The lighting man will derive from them the knowledge that a lighting system or a lighting level are not things to be planned apart and without co-operation with the artist.

We have already mentioned the fact that since time immemorial man has more or less consciously played on these human reactions. This is quite natural, because the way we are seeing has not changed since the origin of mankind.

There has always been one group of persons to whom seeing, and constantly analysing what they see, has been the most important part of their activities. I mean here the painters who have always sought fascinating and pleasing scenes which they could project through the filters of their artistic minds on to the canvas. It is indeed a very interesting experience to go through a picture gallery and to analyse how far the different works of art are based on one or more of the principles we have just described. We have found that most of the pictures which have really been composed as works of art and which have no other aim, show more or less the fundamental schemes of colour, line and brightness (Figs. 8 and 9).

Our next task was to try to bring these theories to the public and to discuss them with the artists and lighting men.

We were very fortunate in 1950 when we were able to install at Eindhoven a kind of museum in a small old factory in which the industry started to make lamps in 1891. There we had the opportunity to incorporate in the building the demonstrations and experiments we needed in order to prove our theories and to demonstrate them

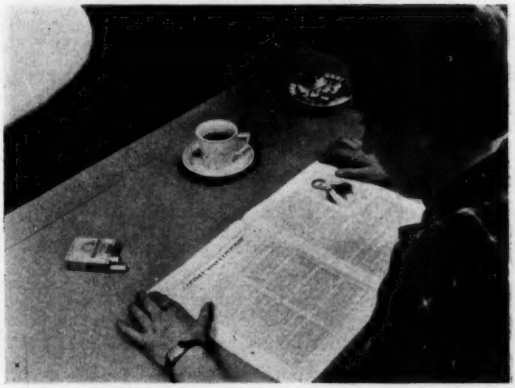

Fig. 13. The line-colour-brightness scheme of a person reading in one of the test rooms.

to other people. This " Demonstration Laboratory " was inaugurated in May, 1951, and it has worked now for over a year. Many hundreds of people have seen the experiments, contributing by their reactions to our knowledge. From these reactions we think we have good grounds for believing that we are working in the right direction. Besides many other demonstrations, concerning shadows, colours and visibility, etc., we made a booth in which the already mentioned colour schemes are visible in a niche (Fig. 10). They can be illuminated to different levels, and being in the shape of little metal doors the different schemes can be observed one after the other by simply turning over two panels like the leaves of a book. Successively we give schemes that are correct, and others that in one way or another are not in keeping with our theories and then we ask the preference of the observer.

The effect of changing the brightness ratios of the surfaces of walls, ceiling, desks and other objects is shown in the photographs of Figs. 11 and 12. Fig. 11 shows the

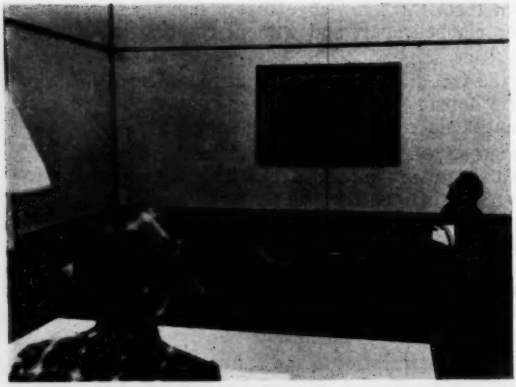

Fig. 14. View of person referred to in Fig. 13 when looking up in room with white walls, flat lighting and distracting picture.

Fig. 15. As Fig. 14 but with warm coloured table tops, cool green walls and a 'concentrated' picture emphasized by local lighting.

distracting brightness of the upper part of the wall caused by the row of lighted panels in the ceiling. This is one of the typical drawbacks of a "louverall" ceiling. In Fig. 12 the upper part of the wall is much less bright and distracting.

We also have a room in which the whole colour scheme can be changed. The walls are in the form of rotatable panels, finished in white, a dull green and in elm-wood. The tops of the tables can revolve and so take the colour of the elm-wood or the green walls. Several "double" pictures hang in this room; the fronts of the pictures have a colour and line composition which obey the rules of our colour schemes, while the backs have opposite arrangements.

By changing the lighting systems and the colours and reflections of walls and pictures, different aspects and atmosphere can be shown to visitors in this room, and their preference for certain combinations of colours and brightnesses determined (Figs. 13-15).

In another room, equipped with very simple furniture but with many lighting possibilities, it can be shown that good lighting of the visual task alone is insufficient and that a second relation between the observer and the room is necessary and can be obtained by creating a second centre of interest in the corner of the room, opposite to the observer. This is a very striking demonstration, and most of the visitors come

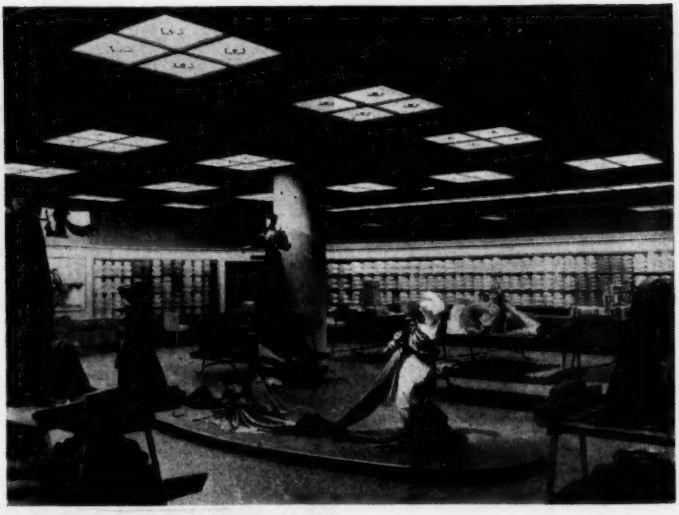

Fig. 16. Lighting in a large store at Rotterdam.

to a conclusion identical to ours, that atmosphere in a room can be obtained only by creating different centres of interest.

We are fully aware of the fact that these efforts can only give a small number of very general and sometimes vague rules, and we know that these rules have to be very general to be accepted by a high percentage of observers, but we do not think that such rules are the most important results of our work.

For example, we think that it is possible to find more precise indications of what

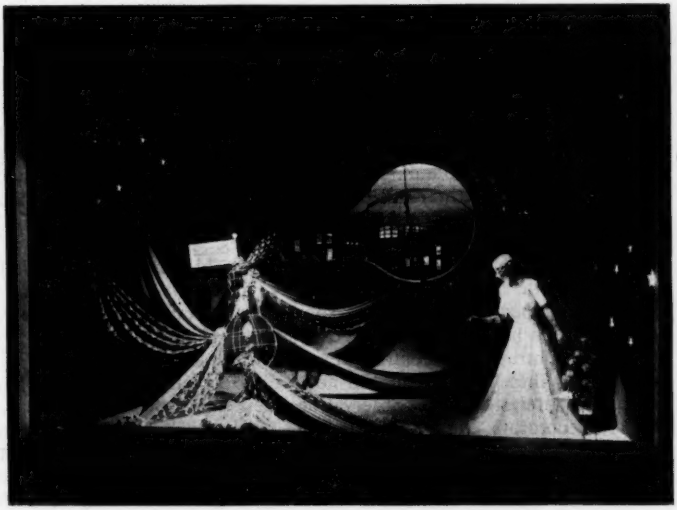

Fig. 17. Lighting of a show window.

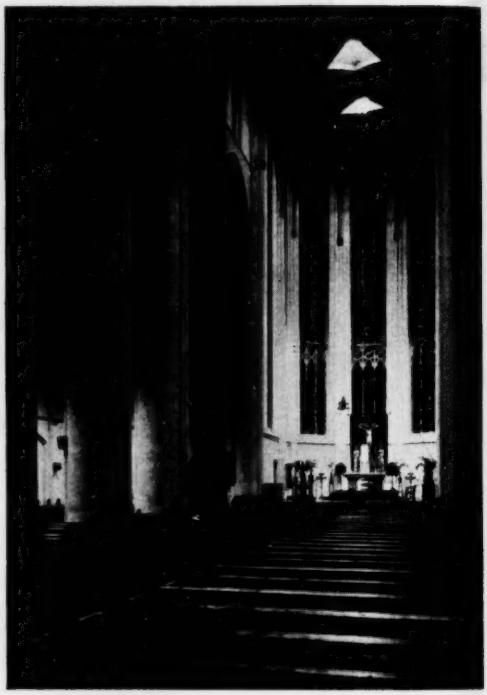

Fig. 18. Lighting of a church interior.

generally leads to comfortable seeing. Consider, for instance, the general rule in brightness engineering that no discomfort is caused by contrasts provided that the brightness ratio of simultaneously seen objects and surfaces does not exceed 3 : 1. This very general rule is misleading because one is led to think that whenever these ratios prevail the conditions are comfortable to the eyes. This is certainly not true. For instance, a white room with white furniture and very diffuse lighting is a completely impossible surrounding for comfort. On the contrary we find in comfortable rooms with two or three shaded lamps very satisfactory conditions, although the brightness ratios greatly exceed 3 : 1. A good impression largely depends on the brightness gradation between adjacent surfaces.

In order to get an idea of what is comfortable in this respect we have constructed spectacles with different sets of glasses, in which light-absorbent materials form differently shaped optical wedges, some being circular and some parallel. We think we have found here a means of determining to what extent, and with what gradations, brightness contrasts can contribute to comfortable seeing.

Even if these experiments do not lead to generally acceptable and easy-to-handle rules, the interest in the observations generally shown by artists, architects and interior decorators and also by lighting experts will be a very useful and necessary contribution to bringing the two groups together and enabling them to understand each other's problems, interests and limits. It is for that reason that we think it useful to proceed on our way, and we should like our colleagues to think these things

over and see if they can, by their experiments and observations, co-operate in finding a deeper understanding of what visual comfort really means.

The results of these studies have not been deduced from theoretical observations only. We can indicate in the lighting practice in Holland of the last five years many remarkable instances in which the lighting problems have been tackled with the line-colour-brightness schemes of which we have spoken as a background.

We can show a number of practical applications of this technique. There is a large store in which the merchandise is emphasised by the light in such a way that it has become the brightest object in the visual field of the buyer (Fig. 16). The ceiling is completely dark with the light concentrated on the tabletops, showcases and the displays on the walls; even the space for circulation is left in a semi-darkness—its illumination being only a half or third of that on the goods. The same principles are illustrated in the lighting of the show-window shown in Fig. 17. We can also show a few churches (Fig. 18) in which the brightness pattern is based entirely on the scheme described, and also different offices and factories.

Every lighting man and every architect or decorator who finds these thoughts of interest will agree that studies on colour and recommendations for colour schemes, as they have for instance been made in this country by the Colour Council, are just as one-sided and incomplete as the recommendations for lighting levels and the prescriptions to avoid discomfort given by the lighting men.

Once more, if we can bring together those groups of experts who think along completely different lines, much will already be achieved because, after all, everyone is seeking a higher level of human comfort.

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